MASTER OF PHILOSOPHY

Ride model analysis - the development of motorcycle suspension damping to optimise vehicle grip through vehicle dynamics fundamental model formulations

Apicella, Michael

Award date:
2013

Awarding institution:
Coventry University

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By

Michael Apicella

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A thesis submitted in partial fulfilment of the University's requirements for the Degree of Master of Philosophy/Master of Research

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Abstract

This document demonstrates the use of simulation and Analysis software such as Mathworks Matlab and Microsoft Excel to gain a greater understanding of suspension characteristics. It focuses on the modelling aspect of a motorcycle vehicle model, and the developments made to the model due to progressive results. The purpose of this project is to create a parametric vehicle model capable of analysing the damping characteristics in relation to tyre grip due to actions on the vehicle, for example, road inputs and operator inputs. This project met its requirements through the use of Mathworks Matlab Simulink and an extensive study of relevant research through the created vehicle model within Microsoft Excel. The research analysed two types of road inputs and two types of operator inputs. The method used, analysed the grip results of each action on the vehicle separately and optimised the damping using Microsoft Excels Solver tool to find the best results. The project then progressed to combine the inputs acting on the vehicle to simulate real life application and validated results such as braking, with real data obtained through external data logging. Through multiple Microsoft Excel simulations this research determines specific damping adjustments for front and rear suspension in order to maintain tyre grip whilst braking at different pressures and banking at different angles. The project concludes that for the given vehicle parameters that a damper delay rate of 3ms can increase the average tyre grip by an average of 13.5%. The main conclusions drawn from the project are that in order to maintain maximum tyre grip (regardless to weather it is front or rear tyre grip) the damping has to be adjusted dependent on the scenario. The nature of this document is not solely useful to motorcycles as the model formulation is directly relevant to the car industry because the same approach can be used, and the document supplies the foundation knowledge for creating 7 and 14 Degree of Freedom models to analyse a four wheeled vehicle.

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Acknowledgements

Damian Harty – provided guidance with simulations to ensure the models reacted as expected along a baseline setting.

Gary Wood – for continuous support throughout the project

Be Wiser Kawasaki Super Stock Team – for supplying the vehicle parameters and allowing me to use the data logged data obtained from racing within the British Superbike Championship in my work.

Nomenclature

m_t	-	Total Sprung Mass	-	kg
a	-	Front Distance to COG	-	m
b	-	Rear Distance to COG	-	m
h	-	Height to COG	-	m
ε	-	Caster Angle	-	Degrees
K_{fs1}	-	Front Sprung Spring Left Leg	-	N/m
K_{fs2}	-	Front Sprung Spring Right Leg	-	N/m
K_{fseff}	-	Effective Front Sprung Spring	-	N/m
K_f	-	Simple DOF's Sprung Spring Stiffness	-	N/m
C_s	-	Simple DOF's Sprung Damping	-	Ns/m
C_{fsc}	-	Front Sprung Compression	-	Ns/m
C_{fsr}	-	Front Sprung Rebound	-	Ns/m
K_{fu}	-	Front Tyre Stiffness	-	N/m
C_{fu}	-	Front Tyre Damping	-	Ns/m
K_u	-	Simple DOF's Unsprung Spring Stiffness	-	N/m
C_u	-	Simple DOF's Unsprung Damping	-	Ns/m
$Z_{fclimit}$	-	Front Sprung Compression Travel Limit	-	mm
$Z_{frlimit}$	-	Front Sprung Rebound Travel Limit	-	mm
m_{fs}	-	Front Sprung Mass	-	kg
m_{fr}	-	Rear Sprung Mass	-	kg
m_{fu}	-	Front Unsprung Mass	-	kg
m_{ru}	-	Rear Unsprung Mass	-	kg
K_{rs}	-	Rear Sprung Spring	-	N/m
C_{rsc}	-	Rear Sprung Compression	-	Ns/m
C_{rsr}	-	Rear Sprung Rebound	-	Ns/m
K_{ru}	-	Rear Tyre Stiffness	-	N/m

C_{ru}	-	Rear Tyre Stiffness	-	N/m
I_{yy}	-	Approximate Vehicle Pitch Inertia	-	$kg.m^2$
d_{p1}	-	Diameter of Front Brake Piston (1st Pair)	-	m
d_{p2}	-	Diameter of Front Brake Piston (2nd Pair)	-	m
d_{disc}	-	Front Brake Disc Outer Diameter	-	m
h_{pad}	-	Front Brake Pad Radial Depth	-	m
g_{pad}	-	Distance from Front Brake Disc outer to Pad Outer	-	m
μ_{pad}	-	Front Brake Pad Coefficient of Friction	-	Ratio
d_{ma}	-	Front Master Cylinder Diameter	-	m
t_{fw}	-	Front Tyre Width	-	mm
t_{fa}	-	Front Tyre Aspect Ratio	-	Ratio
t_{fd}	-	Front Rim Diameter	-	Inch
t_{rw}	-	Rear Tyre Width	-	mm
t_{ra}	-	Rear Tyre Aspect Ratio	-	Ratio
t_{rd}	-	Rear Rim Diameter	-	Inch
μ_{ground}	-	Ground Coefficient of Friction	-	Ratio

Glossary of Terms

mm	-	Millimetre
COG	-	Centre of Gravity
DOF	-	Degree of Freedom
Pitch	-	The Longitudinal Rotational Movement of a Vehicle
hz	-	Hertz
Hertz	-	Measurement of Frequency
SAG	-	Static Displacement of a Vehicle

1.0 INTRODUCTION

This report will show an analytical approach to motorcycle suspension characteristics, and will focus on the effects of motorcycle suspension damping to improve grip between the tyre and the road. The project will directly benefit the motorsport and motorcycle industry; however, the project will produce results which are directly transferable to the whole motorcycle industry, including motorcycle manufactures.

The report goes through the process of creating multiple Excel spread sheets in order to simulate vehicle models. This document shows the process in which the model develops over time and shows the implementation of the model into Mathworks Matlab Simulink software.

The Mathworks Matlab Simulink Models will be used as confirmation to determine whether the Microsoft Excel model has been created successfully and vice versa, this is not in any way stating that Simulink is not capable of creating a working model, it is suggesting that the knowledge of the programmer has more experience in using Microsoft Excel than Mathworks Matlab Simulink.

2.0 OBJECTIVES

The process of the study will be performed as followed;

- Microsoft Excel spread sheet
    - Creating a parametric Microsoft Excel document capable of showing both suspension movement and wheel movement of a ¼ vehicle model.
    - Developing the Microsoft Excel document to show the vehicle model over a step profile of 100mm
    - The implementation of a random road profile to the vehicle model.
- Simulink Model
    - Creating vehicle models simulations showing both suspension movement and wheel movement.
    - Development of the vehicle models showing the suspension movement and wheel movement over a 100mm step profile
    - Further development of the vehicle model showing the suspension movement and wheel movement over a random road profile.
- Damping Adjustments
    - The adjustment of the damping in within the models, from maximum values, to minimum values.
    - Comparing the results between the Microsoft Excel simulations and the Mathworks Simulink simulations.
    - Adjusting the damping values within the model by small increments to determine optimum grip within the tyre.
- Full Motorcycle Vehicle Model
    - Creating a full 5DOF motorcycle vehicle model within Microsoft Excel which possesses the capability of being able to use real time data in order to represent vehicle heave, and pitch.
    - Studying the effects braking, Step profiles and random road profiles have on the grip performance.
    - Modifying the damping of the vehicle when put through various step profiles, random road, braking scenarios and banking scenarios to optimise grip performance based on indexes
    - To analyse the effects of damper delay rates on the indexes.

- Determine an optimised damper delay rate for the system and optimise the damping for each scenario.

The results of each section will be presented and discussed as they are found throughout the report to show the natural progression of the project.

3.0 LITERARY REVIEW

During the initial stage of the investigation, a number of areas under the title of Ride Model Analysis were explored. Through this study, the fundamental knowledge on motorcycle dynamics and analysis has been developed. Details of vehicle modelling techniques in respect to damping control have been discussed throughout the report in there relevant chapters. The aim of this chapter is to provide a summary of the given areas in order to determine the most appropriate route for modelling.

The following sections within this chapter are summaries of the relevant information found during the investigation and are used to demonstrate what methods are currently available and its relevance to the study..

3.1 Review of Mechanical Vibrations for Engineers (Lalanne, et al., 1984)

This book gives a good overview of mechanical engineering. The author starts the book off with talking about 1 degree of freedom system, covering simple equations of motion for free vibration, and the basic phenomena of mechanical vibrations such as resonance, damping and forced response. However, the author quickly moves away from the equations of motions formulation and towards exponential equations, using the angular frequency and viscous damping ratio in order to determine a characteristic equation ratio. Using this characteristic ratio the author is able to calculate the response maxima. The author goes onto discus two and N-DOF (Degree of Freedom) on pages 38-42 and 65-95 for free vibration. The then book moves the modelling approach to that of a matrices formulation which consists of Jacobian matrices to determine the results. On pages 5-13, the author presents a step by step solution to modelling a one degree of freedom forced response function, which could be directly transferred into Microsoft Excel to create a displacement vs time graph. The harmonic excitation within this part of the book is particularly vague, yet the author continues with forced vibration on pages 42-45. However, they focus on the transmissibility of the system rather than the physical displacement and forces acting on the system. Mechanical Vibrations for Engineers shows a variety of useful exercises for modelling different vibration systems. The book tends to focus the solution towards the study of transmissibility, although ‘Exercise 14’ does show a useful step-by-step approach to modelling the displacement response when a 1DOF system is subjected to a constant force. The book gives a large quantity of script for computer modelling on pages 196-260. Due to the age of the book the computer language within the book is not used within the intended modelling software proposed in section '1.0 INTRODUCTION'. Therefore, the information regarding programing proves irrelevant within this book.

3.2 Review of Vibration: With Control, Measurement and Stability (Inman, 1989)

Vibration: With Control, Measurement and Stability provided minimal information into the solution to free vibration. However, the author does give a brief description explanation using Euler's formulas to create displacement vs time graphs. Pages 4-7 provide an insight into damping and its involvement within a system. The book develops onto give simple step-by-step approach to modelling the displacement response of a 1DOF damped system. Pages 7-11 provide good detail to obtain transmissibility graphs and then it progresses onto a step response of a 1DOF system. In spite of this, the approach to obtaining the provided graphs is not given clearly as only a final solution is provided. Inman provides no direct code of method for computer simulation of his models. However, due to the mathematical approach in which the book takes to solve solutions, using matrices, the implementation of the methods into programs such as MATLAB/Simulink can be accomplished without too much difficulty.

3.3 Review of Engineering Vibration (Inman, 1994)

Inman gives worked a solution for a 1DOF system with known values for initial displacement and initial velocity. The author uses the equation of motion for a spring-mass system to generate a displacement vs time graph and uses known nomenclature on pages 3-8. Between pages 17-23 the book gives explanations for under-damped, over-damped and critically damped 1DOF systems. The author uses Euler formulations to solve for each scenario. However, each methodology is slightly different to achieve the provided results within the book. The book then goes onto explain, a step-by-step approach to a 2DOF free vibration system using matrices much later within the book on pages 158-168. On pages 61-66 the book states an approach to the response of an un-damped 1DOF system. This approach shows that the response is driven, and increases over time. Therefore, it can be assumed that the formulation is a resonant response function. The book goes onto provide an impulse response function which can be seen as a bump in the road and an arbitrary response function which can be otherwise defined as a step in the road, on pages 113-126. These two functions are both provided for an un-damped 1DOF system.

From the decaying sine wave provided within the graph, it can be established that there is likely to be some sort of damping in within the system, no matter how small it may be. Worked ‘Example 3.2.1’ within the book provides a solution for no damping and damped responses to an arbitrary periodic input function. This function is slightly more complex than the previous example within the book and not explained in as much depth, and the periodic input could be replacement with a given road profile to create a 1DOF response of a quarter vehicle model without too much complexity. Inman provides a ‘Matrix Basics’ chapter, between pages 530-535, which will prove useful for implemented MATLAB code, as MATLAB is a powerful mathematical tool which is capable of solving matrices quickly and efficiently. The author also provides a set of tools on a separate floppy disc. However, the floppy disc is long since redundant and no longer with the book. Therefore, the tools cannot be interrogated within this report.

3.4 Review of Vibration Engineering (Dimarogonas, 1938)

Dimarogonas uses Cramer’s Method for determining the displacement of 2DOF systems between pages 343-353. The book provides worked examples for forced vibration of a sinusoidal force. The book goes onto describe periodic excitation and random excitation with explained worked examples. ‘Fourier Transform’s’ are used to model any periodic function of the displacement against time. The approach to the solution is not well documented and proves difficult to follow. It can be seen that the author provides a complete solution of the problem for a sinusoidal force on pages 74-92. However, the nomenclature used is different compared to other analysed books. As it is recommended to use only one type of nomenclature the mathematical approach would need establishing prior to implementing the process. This is not a statement that the method is neither accurate nor invaluable, solely a statement that the more commonly found nomenclature should be used to prevent confusion when implementing and interrogating the mathematical model. Dimarogonas finishes up the book with a chapter named ‘Special Methods for Computer Aided Vibration Analysis’ between pages 386-428. Within this section the author provides pseudo code for implementing ‘Rayleigh’s’ method and also shows a variety of matrices to solving there solutions which could be transferable to mathematical software programs such as MATLAB/Simulink.

3.5 Review of Motorcycle Dynamics (Cossalter, 1947)

Vittore Cossalter provides a lot of information throughout the book about motorcycle dynamics. In respect to suspension dynamics and mathematically representing the displacement of the masses of the system, the book is rather limited. The book provides information on transmissibility and natural frequency for N-DOF systems, between pages 182-191. Cossalter does not give any equations in regards on equations of motion relating to this project. Later on, pages 194-198 Cossalter demonstrates the approach to the transmissibility and frequency response function. However, there is no detail in regards to degree of freedom models and there given equations of motion, thus, providing no insight into the accelerations, velocities and displacements to which a system will be subjected to, when excited by a defined input.

3.6 Review of The Multibody Systems Approach to Vehicle Dynamics (Blundell & Harty, 2004)

Blundell & Harty provide approaches to analyse the natural frequencies of the systems. The research requires the physical response of the system as a displacement in order to establish effective suspension. The book provides a particular transmissibility graph of a 1DOF system that shows the acceleration vs the frequency of the response. This is essentially a comfort factor graph, as it shows the ride frequency vs the comfort threshold, which could prove useful in order to determine whether performance impedes the comfort of the vehicle. Blundell & Harty provide a lot of information about computer modelling of vehicle systems, and the entirety of their book is based on this. The book works through the methods of using MSC Adams Multibody Systems software to analyse the response of vehicle systems and, therefore, to some extent, the whole book becomes relevant when creating a vehicle model. The more relevant sectors are and can be found on pages 191-202 where the authors explain the process of modelling a 1DOF Spring Damper model and comparing the mathematical results to that of the Multibody system model, and then pages 301-320, which explains the process of modelling a tyre using 'The Magic Formula'.

3.7 Review of Ride Model Calculations (Harty, 2009)

Harty's report 'Ride Model Calculations goes through an analytical approach to improving tyre grip based on the fundamentals of vehicle dynamics. The author uses free body diagrams in order to generate equations of motion in which he uses to determine the response of the vehicle and tyre over given road profiles. The author then uses a grip, heave and pitch index to determine what areas of the adjustments improve the vehicle or reduce the performance. The purpose of this report is to redesign a damper for Óhlins suspension to work on the ProDrive Mini rally vehicles. The report clearly demonstrates the multiple degree of freedom formulations and goes through the explanations of using equations of motions, Laplace transformations and Transfer Functions in order to develop an accurate model.

3.8 Review of Vibration Suppression using Two-Terminal Flywheel. Part II: Application to Vehicle Passive Suspension (Li, et al., 2011)

This paper by Li, et al, presents their findings on the 'Two-Terminal Flywheel' which they present in Part I of this paper, and how they have simulated attaching it in parallel to the suspension strut to suppress vibration and increase comfort. The authors conclude that "the proposed 'Two-Terminal Flywheel' has demonstrated superior passenger comfort and tire grip, with equal suspension deflections" (Li, et al., 2011). Therefore, further investigation into their grip index on page 1356 of the journal is required. The author's state that the performance criteria for the model is defined from the 'Journal of sound and Vibration', paper named 'Numerical assessment of fore-and-aft suspension performance to reduce whole-body vibration of wheel loader drivers' (Fleury & Mistrot, 2006). The authors also focus their results on its equations of motion, which were generated through free body diagrams, to create a passive suspension model, the authors then use Multibody systems analysis to validate their work.

3.9 Review of Numerical assessment of fore-and-aft suspension performance to reduce whole-body vibration of wheel loader drivers (Fleury & Mistrot, 2006)

Fleury & Mistrot's paper is regarding comfort of post suspension components such as seats. The paper mainly goes through the test results of validating there computational approach to design fore-and-aft suspension for off-road vehicle seats. The paper also goes through the process of modelling a sitting human body which was coupled to a seat model. The relevance of this paper is the performance indicator which works by using the RMS (Route Mean Squared) of the acceleration stating that the lower the value the better the result, which coincides with Harty's grip index approach in 'Ride Model Calculations'. However, Harty takes the reciprocal of the RMS to convert the number to a value between 1 at 10 for simplicity, so that the higher the number the higher the grip.

3.10 Review of the Dynamic Response of Tyres to Brake Torque Variations and Road Unevennesses (Zegelaar, 1998)

Within Zegelaar's thesis, he focuses on the study of in-plane dynamics of the tyre, which deal with the forces and motion within the plane of rotation of the wheel. He uses the 'Flexible Ring Model' to study the tyre behaviour in detail and the 'Rigid Ring Model' is developed within the thesis to be used in vehicle simulations. The Author's results are primarily on the 'effective rolling radius variations of the tyre', and he focuses on this due to the three main responses of the tyre; a variation in the vertical force, the variation in the longitudinal force and a variation in the rotational velocity (Gough, 1963). Zegelaar states, that the variations in effective rolling radius due to road undulations or vertical vibrations of the wheel, induce variations in longitudinal forces and variations in rotational velocity. Therefore, indirectly stating that when the vertical tyre forces vary, there are more forces which act through the tyre due to the effect of alternative responses of the tyre. Zegelaar, proves this in 'Figure 4.8' of his thesis where he shows how the Vertical Tyre Deflection (mm) changes the; Vertical Load (N), Vertical Stiffness (N/mm), Longitudinal Stiffness (N/mm), Longitudinal Stiffness (N/mrad) and Effective Rolling Radius (mm).

3.11 Review of Unsprung Mass with In-Wheel Motors – Myths and Realities (Anderson & Harty, 2013)

This paper by Anderson & Harty focuses on the unsprung mass as an important parameter in ride and handling behaviour. The authors develop a scale based measurement equation similar to that of the Cooper scale which states 1 is best and 10 is worst. However, unlike the Cooper scale, the Anderson & Harty scale, named KPI (Key Performance Index) works in reverse stating that 0 is the worst and 10 is excellent, although it is still possible for the KPI to fall outside of these ranges. The KPI index presented within this paper conforms to ISO 2631 (International Standard, 2009) which states the comfort thresholds as 0-3Hz for 1 hour exposure for primary ride and above 3Hz for 1 hour exposure for secondary ride. The equations for this KPI are given in 'Figure 3-1' and have been taken from 'Section 5.1 Ride' of Anderson & Harty's paper.

5.1 Ride

Primary Ride is enumerated using RMS sprung mass vertical acceleration filtered to pass 0-3Hz using a 4 pole Butterworth filter with zero phase shift:

$$KPI = \left(5 - \sqrt{\frac{\int_0^t \left(filt(\ddot{z}_s) \right)^2 dt}{t}} \right) \cdot 2 \qquad (1)$$

Secondary Ride is very similar, but filtered to pass data above 3Hz and scaled differently:

$$KPI = \left(3 - \sqrt{\frac{\int_0^t \left(filt(\ddot{z}_s) \right)^2 dt}{t}} \right) \cdot \frac{10}{3} \qquad (2)$$

Figure 3-1 - Anderson & Harty's KPI Comfort Index (Anderson & Harty, 2013)

4.0 RIDE MODEL ANALYSIS

4.1 Vehicle Parameters

As the main purpose of the report is to benefit motorcycle suspension, the parameters will be based on motorcycle values, and considering that the report will analyse ¼ vehicle models as well as a full vehicle model, only the parameters for the front of the vehicle will be used when modelling the ¼ vehicle model. The motorcycle values given below are that of the 'Be Wiser Kawasaki British Super Stock Team's' ZX10R and have been provided by the team members (Be Wiser Kawasaki British Super Stock Team, 2013). The thesis demonstrates a progressive approach to the conclusions. The reason a ¼ vehicle model has been used is to show the developmental approach to the solution, this way each step can be validated through to the end result, to ensure the project is kept on track and in the correct direction.

Vehicle Parameters

m_t	-	Total Sprung Mass	160	kg
a	-	Front Distance to COG	0.6	m
b	-	Rear Distance to COG	0.8	m
h	-	Height to COG	0.8	m
ε	-	Caster Angle	24	Degrees
K_{fs1}	-	Front Sprung Spring Left Leg	38640	N/m
K_{fs2}	-	Front Sprung Spring Right Leg	40674	N/m
K_{fseff}	-	Effective Front Sprung Spring	$(K_{fs1}+K_{fs2})$	N/m
K_f	-	Simple DOF's Sprung Spring Stiffness	38640	N/m
C_s	-	Simple DOF's Sprung Damping	3000	Ns/m
C_{fsc}	-	Front Sprung Compression	2500	Ns/m
C_{fsr}	-	Front Sprung Rebound	3000	Ns/m
K_{fu}	-	Front Tyre Stiffness	400000	N/m
C_{fu}	-	Front Tyre Damping	300	Ns/m
K_u	-	Simple DOF's Unsprung Spring Stiffness	400000	N/m
C_u	-	Simple DOF's Unsprung Damping	400	Ns/m
$Z_{fclimit}$	-	Front Sprung Compression Travel Limit	0.1	m
$Z_{frlimit}$	-	Front Sprung Rebound Travel Limit	0.028	m
m_{fs}	-	Front Sprung Mass	(mt*b)/(a+b)	kg
m_{fr}	-	Rear Sprung Mass	(mt*a)/(a+b)	kg
m_{fu}	-	Front Unsprung Mass	18	kg

m_{ru}	-	Rear Unsprung Mass	15	kg
K_{rs}	-	Rear Sprung Spring	100000	N/m
C_{rsc}	-	Rear Sprung Compression	2500	Ns/m
C_{rsr}	-	Rear Sprung Rebound	3000	Ns/m
K_{ru}	-	Rear Tyre Stiffness	300000	N/m
C_{ru}	-	Rear Tyre Stiffness	350	Ns/m
I_{yy}	-	Approximate Vehicle Pitch Inertia	$m_s+m_{fu}+m_{ru}$	
d_{p1}	-	Diameter of Front Brake Piston (1st Pair)	0.027	m
d_{p2}	-	Diameter of Front Brake Piston (2nd Pair)	0.027	m
d_{disc}	-	Front Brake Disc Outer Diameter	0.32	m
h_{pad}	-	Front Brake Pad Radial Depth	0.06	m
g_{pad}	-	Distance from Front Brake Disc outer to Pad Outer	0	m
μ_{pad}	-	Front Brake Pad Coefficient of Friction	0.35	Unitless
d_{ma}	-	Front Master Cylinder Diameter	0.0091	m
t_{fw}	-	Front Tyre Width	120	mm
t_{fa}	-	Front Tyre Aspect Ratio	70	Unitless
t_{fd}	-	Front Rim Diameter	17	Inches
t_{rw}	-	Rear Tyre Width	190	mm
t_{ra}	-	Rear Tyre Aspect Ratio	50	Unitless
t_{rd}	-	Rear Rim Diameter	17	Inches
μ_{ground}	-	Ground Coefficient of Friction	0.97	Unitless

The given damping values within this section have been obtained through from 'Damian Harty's Ride Model Calculation' report (Harty, 2009), the report states 3Ns/mm of compression damping provides good grip optimisation. Therefore, the value of 3Ns/mm has been taken as a starting point for the model. The physical damping values of the 'Be Wiser Kawasaki' ZX10R were not available as the damper testing facilities are not present for the team, and the team works in values of 'clicks' in range of adjusting the suspension damping, all other data has been obtained through physically measuring the equipment by the team or obtained from the vehicle's manufacturer's website (Kawasaki UK, 2013).

4.2 Free Body Diagrams

This section demonstrates the use of free body diagrams to determine the forces acting through the systems so that the correct equations can be used within the modelling process.

4.2.1 1 Degree of Freedom System

'Figure 4-1' shows that of a 1 degree of freedom model and from this we can see the static displacement of a mass supported by a spring damper system. The given system shows a solid ground so that there are no external forces acting on the mass other than the gravity and the provided equation of motion shows this. The equations of motion within this section of the report have been written largely by inspection of the accompanying Free Body Diagrams.

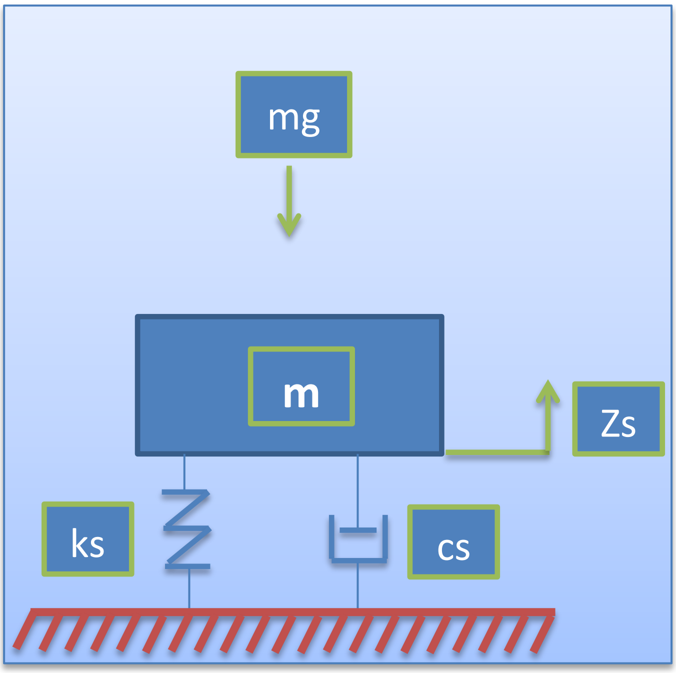

Figure 4-1 - 1 Degree of Freedom System Free Body Diagram

Equation 4-1 - 1 DOF Equation of Motion

$$\boldsymbol{m\ddot{Z}_s\,(t)\,[N]} = (-Z * K_s) + (-\dot{Z}_s * c_s) - mg$$

4.2.2 2 Degree of Freedom System

'Figure 4-2' shows the developed 1 degree of freedom model to include a secondary mass supported on top of the original mass, it includes another spring damper system, which is represented as the sprung mass of a vehicle. It can be seen that the result is that there is an external force acting on the un-sprung mass, which is calculated through as the dynamic force of the sprung mass and has lengthened the equation for the mass connected to the ground. It can be seen that gravity is still included in the equations. However, it has been excluded from the free body diagram.

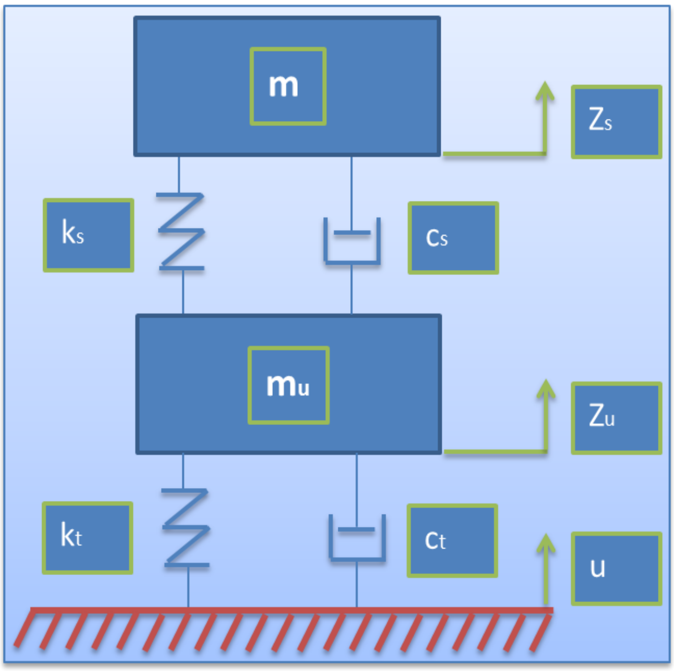

Figure 4-2 - 2 Degree of Freedom System Free Body Diagram

Equation 4-2 - 2 DOF Equation of Motion

$$\boldsymbol{m\ddot{Z}_s(t)}\ [\boldsymbol{N}] = (Z_u - Z_s)k_s + (\dot{Z}_u - \dot{Z}_s)c_s - mg$$

$$\boldsymbol{m_u\ddot{Z}_u}\ (\boldsymbol{t})\ [\boldsymbol{N}] = (-Z_u)k_u + (-\dot{Z}_u)c_u + (Z_s - Z_u)k_s + (\dot{Z}_s - \dot{Z}_u)c_s - mg$$

4.2.3 1 Degree of Freedom System with a Ground Displacement

Figure ‘Figure 4-3’, represents that of the previous 1 degree of freedom model. However, this shows what the influence of vertical ground displacement has on the model and can be shown by U and U’ within the equation. Within all of the Equations of motion the Variables which can affect the characteristics of the system are defined as ‘m’, ‘K’ and ‘C’. These variables are the masses (m) in kg, the stiffness’s (K) in N/m and the damping values (C) in Ns/m. Each value which has been used for the variable has been defined in Section ‘4.1 Vehicle Parameters’ within the thesis

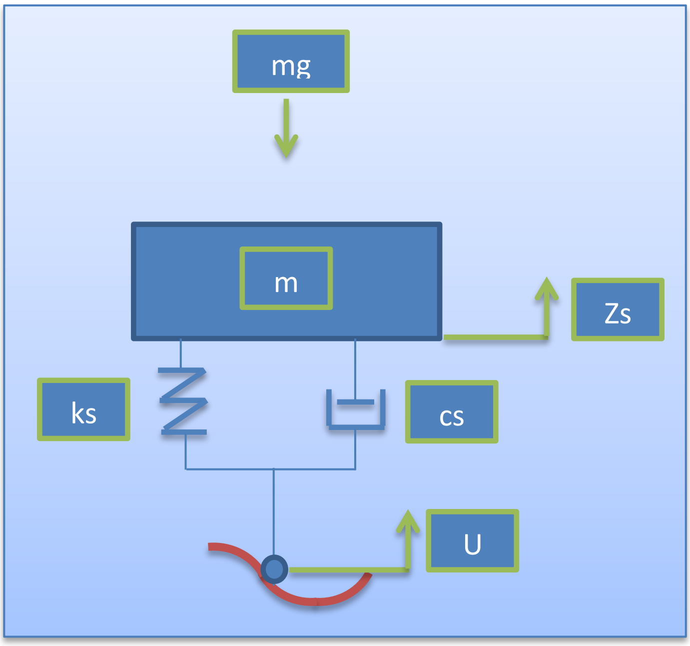

Figure 4-3 - 1 Degree of Freedom System with Vertical Ground Displacement Free Body Diagram

Equation 4-3 - 1 DOF Equation of Motion with Ground Input

$$\boldsymbol{m\ddot{Z}_s\,(t)}\ [\boldsymbol{N}] = (U - Z_s)k_s + \left(\dot{U} - \dot{Z}_s\right)c_s - mg$$

4.2.4 2 Degree of Freedom System with a Ground Displacement

The above diagram shows that of the developed 2 degree of freedom model in section '4.2.2 2 Degree of Freedom System'. It shows how the vertical ground displacement affects the un-sprung mass. It can be seen that the ground displacement does not directly affect the sprung mass as there is no direct connection between the two. However, where the un-sprung mass is effected it induces larger forces onto the 'Ks' and 'Cs', which in turn will change the behaviour of 'Zs'. 'Zs' represents the vertical displacement of the sprung mass.

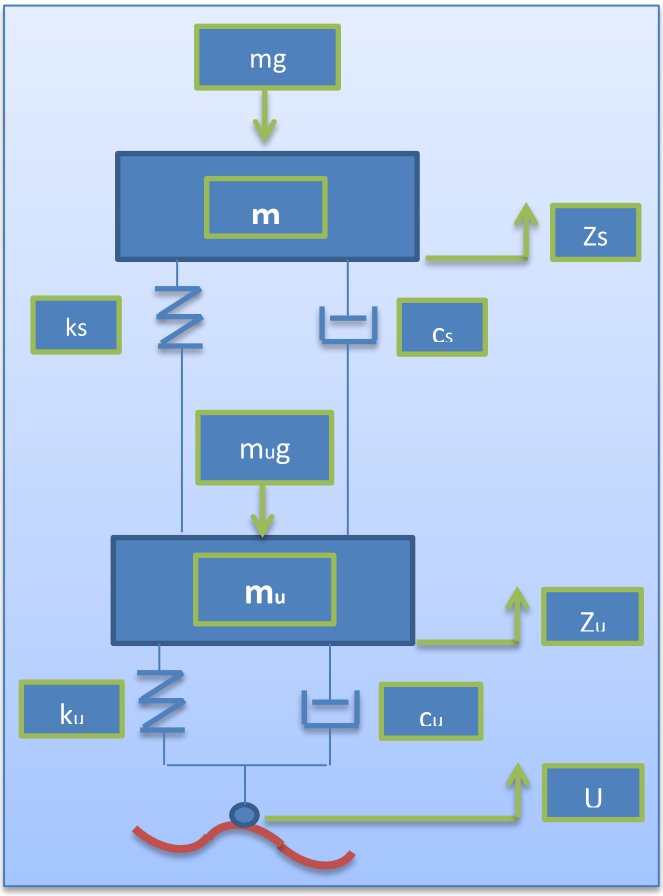

Figure 4-4 - 2 Degree of Freedom System with Vertical Ground Displacement Free Body Diagram

Equation 4-4 - 2 DOF Equation of Motion with Ground Input

$$\boldsymbol{m\ddot{Z}_s(t)}\ [\boldsymbol{N}] = (Z_u - Z_s)k_s + (\dot{Z}_u - \dot{Z}_s)c_s - mg$$

$$\boldsymbol{m_u\ddot{Z}_u}\ (\boldsymbol{t})\ [\boldsymbol{N}] = (U - Z_u)k_u\ + (\dot{U} - \dot{Z}_u)c_u + (Z_s - Z_u)k_s +$$
$$+(\dot{Z}_s - \dot{Z}_u)c_s - m_u g$$

4.3 Excel Model Building

4.3.1 Excel Calculations

Prior to creating the Microsoft Excel spread sheet, the correct calculations need to established from the free body diagrams, so that, the displacement of the masses (Zs = Suspension movement and Zu = Wheel Movement) can be obtained.

From taking the Equations of Motion for the 2 DOF system we can find the displacement as shown below;

Equation 4-5

$$\boldsymbol{m\ddot{Z}_s(t)[N]} = (Z_u - Z_s)k_s + (\dot{Z}_u - \dot{Z}_s)c_u - mg$$

Equation 4-6

$$\boldsymbol{m_u\ddot{Z}_u}\ (\boldsymbol{t})[\boldsymbol{N}] = (-Z_u)k_u + (-\dot{Z}_u)c_u + (Z_s - Z_u)k_s + (\dot{Z}_s - \dot{Z}_u)c_u - mg$$

If:

$$\sum \boldsymbol{F_s} = m\ddot{Z}_s \qquad \text{and} \qquad \sum \boldsymbol{F_u} = m\ddot{Z}_u$$

Then the Acceleration of the sprung and un-sprung masses are;

Equation 4-7

$$\boldsymbol{\ddot{Z}_s(t)[m/s^2]} = \frac{(Z_u - Z_s)k_s + (\dot{Z}_u - \dot{Z}_s)c_u - mg}{m}$$

Equation 4-8

$$\boldsymbol{\ddot{Z}_u(t)[m/s^2]} = \frac{(-Z_u)k_u + (-\dot{Z}_u)c_u + (Z_s - Z_u)k_s + (\dot{Z}_s - \dot{Z}_u)c_u - mg}{m_u}$$

The velocities can then be found through Numerical Integration as shown below;

Equation 4-9

$$\boldsymbol{\dot{Z}_s[m/s]} = \dot{Z}_{s-1} + \left(\left(\frac{(\ddot{Z_{s-1}} + \ddot{Z}_s)}{2}\right) * (t - t_{-1})\right)$$

Equation 4-10

$$\boldsymbol{\dot{Z}_u[m/s]} = \dot{Z}_{u-1} + \left(\left(\frac{(\ddot{Z_{u-1}} + \ddot{Z}_u)}{2}\right) * (t - t_{-1})\right)$$

The displacements can be found by further Numerical Integration;

Equation 4-11

$$\boldsymbol{Z_s[m]} = Z_{s-1} + \left(\left(\frac{(\dot{Z}_{s-1} + \dot{Z}_s)}{2}\right) * (t - t_{-1})\right)$$

Equation 4-12

$$\boldsymbol{Z_u[m]} = Z_{u-1} + \left(\left(\frac{(\dot{Z}_{u-1} + \dot{Z}_u)}{2}\right) * (t - t_{-1})\right)$$

This process can now be used for each Equation of Motion so that the displacement can be determined

4.3.2 Simplified Excel DOF Calculations

The calculations can be split up into relevant sections to make problem solving easier. Considering there should be a step rate of approximately 1,000 Hz, and the equation can become rather long within excel, it is good practice to reduce the equation size per cell.

When modelling the ‘Degrees of Freedom with a Step Profile’, it can be useful to include ‘SAG’ so that the wheel and suspension graphs follow the trend of the step profile graph. Therefore, the Equations of Motion with ‘SAG’ included can be broken down, and determined as followed;

Equation 4-13

$$\boldsymbol{Sprung\ Weight\ force}\ [\boldsymbol{N}] = mg$$

Equation 4-14

$$\boldsymbol{Sprung\ Spring\ Force}[\boldsymbol{N}] = (Z_u - Z_s)k_s$$

Equation 4-15

$$\boldsymbol{Sprung\ Damper\ Force}[\boldsymbol{N}] = (\dot{Z}_u - \dot{Z}_s)c_u$$

Equation 4-16

$$\boldsymbol{Sprung\ 'SAG'}[\boldsymbol{N}] = m * -g$$

Equation 4-17

$$\begin{aligned}\boldsymbol{Sprung\ Total\ Force}[\boldsymbol{N}] &= (Sprung\ Weight\ Force) + (Sprung\ Spring\ Force)\\ &+ (Sprung\ Damper\ Force) + (Sprung\ 'SAG')\end{aligned}$$

Equation 4-18

$$\boldsymbol{Sprung\ Acceleration}\ [\boldsymbol{m/s^2}] = \frac{Sprung\ Total\ Force}{m}$$

Equation 4-19

$$\boldsymbol{Sprung\ Velocity}\ [\boldsymbol{m/s}] = Sprung\ Acceleration + \frac{Previous\ Sprung\ Accel + Current\ Sprung\ Accel}{2} * Time\ Increment$$

Equation 4-20

$$\boldsymbol{Sprung\ Displacement}[\boldsymbol{m}] = \ Sprung\ Velocity + \frac{Previous\ Sprung\ Velocity + Current\ Sprung\ Velocity}{2} * Time\ Increment$$

Equation 4-21

$$\boldsymbol{Unsprung\ Weight}\ [\boldsymbol{N}] = m_u g$$

Equation 4-22

$$\boldsymbol{Unsprung\ Spring\ Force}\ [\boldsymbol{N}] = (U - Z_u)k_u + \ (Z_s - Z_u)k_s$$

Equation 4-23

$$\boldsymbol{Unsprung\ Damper\ Force}\ [\boldsymbol{N}] = (\dot{U} - \dot{Z}_u)c_u + (\dot{Z}_s - \dot{Z}_u)c_u$$

Equation 4-24

$$\boldsymbol{Unsprung\ \ 'SAG'}[\boldsymbol{N}] = m_u * -g$$

Equation 4-25

$$\boldsymbol{Unsprung\ Total\ Force}\ [\boldsymbol{N}] = (Unsprung\ Weight\ Force) + (Unsprung\ Spring\ Force) + (Unsprung\ Damper\ Force) + (Unsprung\ 'SAG')$$

Equation 4-26

$$\boldsymbol{Unsprung\ Acceleration}[\boldsymbol{m/s^2}] = \frac{Unsprung\ Total\ Force}{m}$$

Equation 4-27

$$\boldsymbol{Unsprung\ Velocity}[\boldsymbol{m/s}] = Unsprung\ Acceleration + \frac{Previous\ Unsprung\ Accel + Current\ Unsprung\ Accel}{2} * Time\ Increment$$

Equation 4-28

$$\boldsymbol{Unsprung\ Displacement}[\boldsymbol{m}] = Unsprung\ Velocity + \frac{Previous\ Unsprung\ Velocity + Current\ Unsprung\ Velocity}{2} * Time\ Increment$$

From using the above approach it is possible to generate graphs for an equation of motion within Microsoft Excel, clearly the more Degrees of freedom that are being modelled, require more columns within the Microsoft Excel model.

The current method with the given parameters in section '4.1 - Vehicle Parameters', provide the following graphs within excel;

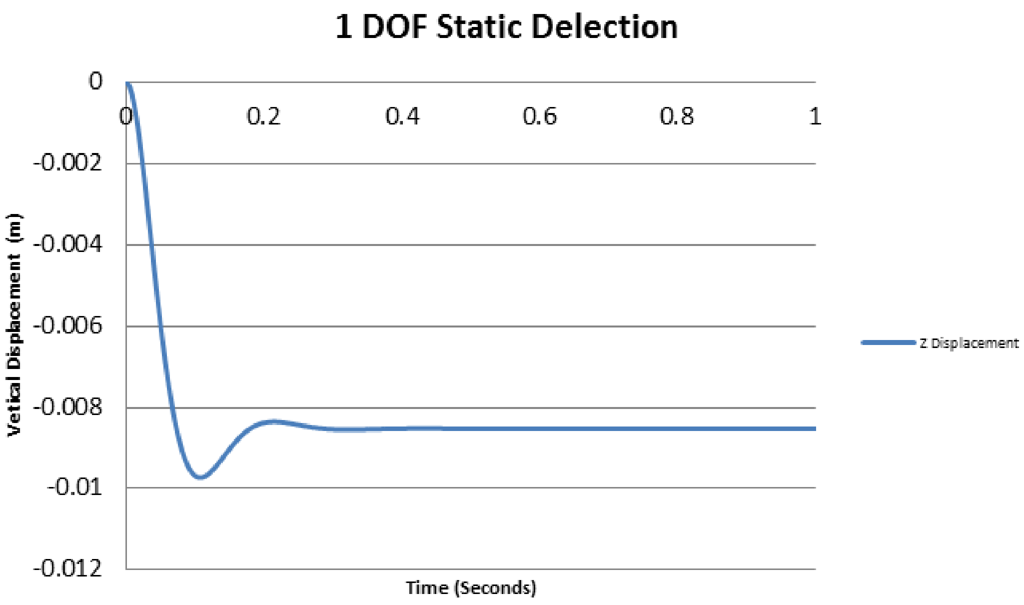

Figure 4-5 - 1 Degree of Freedom Excel Graph

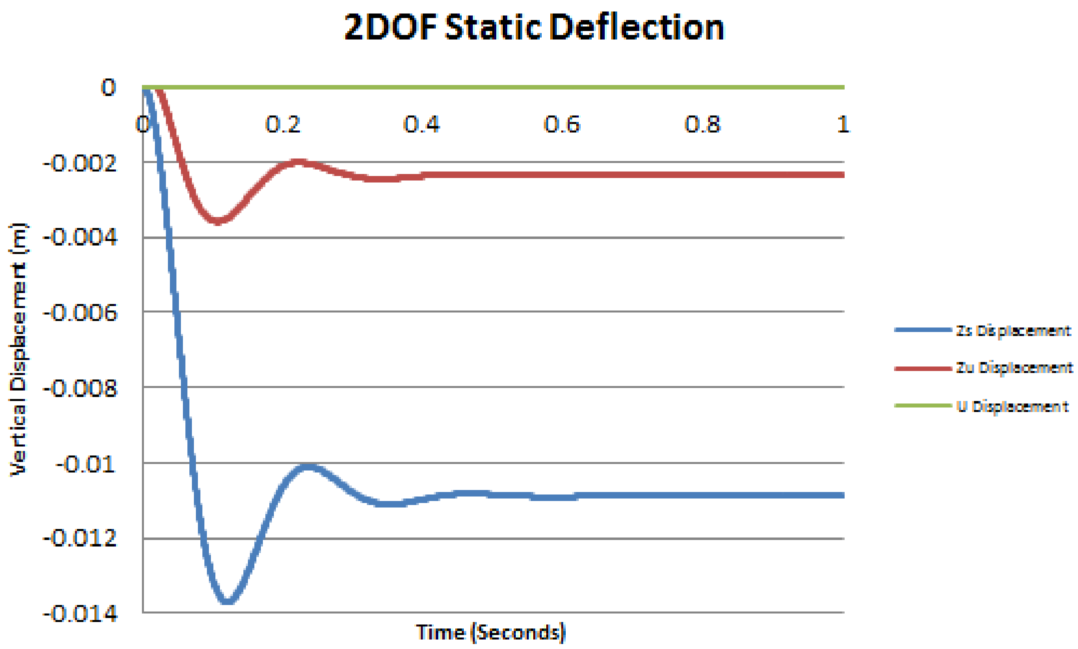

Figure 4-6 - 2 Degree of Freedom Excel Graph

'Figure 4-5 and Figure 4-6', shows that the tyre, represented by 'Zu', affects the movement of the suspension by approximately 5mm. Therefore, it is essential that for the study to be effective, that all relevant conclusions are to be made from a 2 Degree of Freedom system or more.

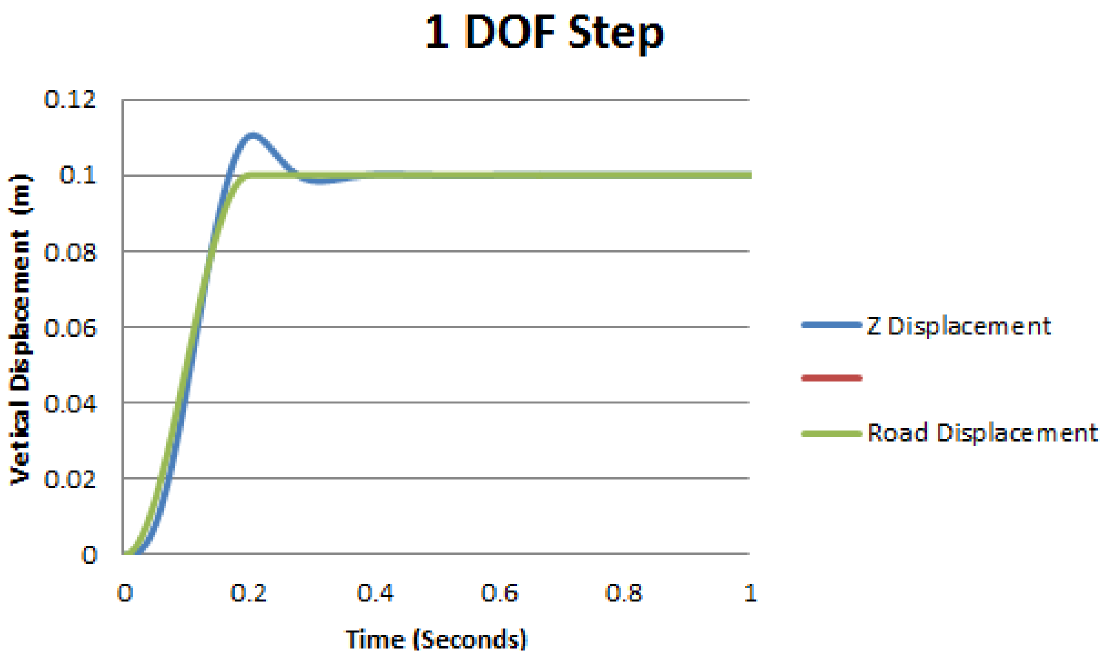

Figure 4-7 - 1 Degree of Freedom with a Step Profile Excel Graph

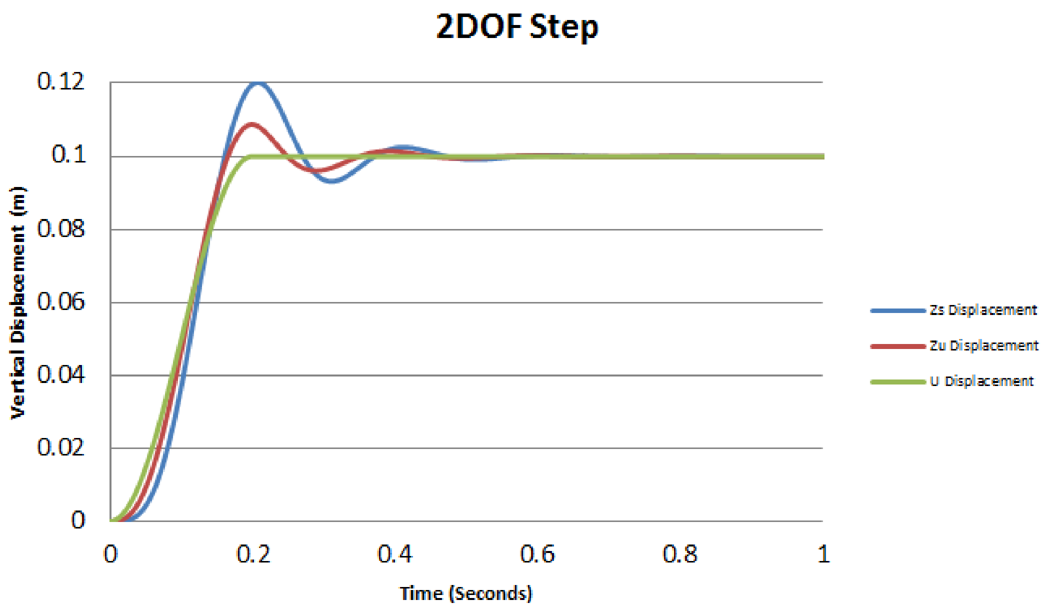

Figure 4-8 - 2 Degree of Freedom with a Step Profile Excel Graph

Similar to the ‘Figure 4-5 & Figure 4-6‘, the peaks shown in ‘Figure 4-8’ for the sprung mass is higher than that of the peaks in ‘Figure 4-7’, with a slightly different shape and more oscillations. This concludes that a 2 Degree of Freedom simulation should be used over a 1 Degree of Freedom model at all times in order to determine more realistic results.

4.4 Simulink Model Building

Now that a base line model has been completed within Microsoft Excel, a Simulink model can be created. This ensures that, if any doubts about the model are present then it can be compared with the Microsoft Excel model to ensure an adequate level of accuracy is maintained.

Simulink uses blocks to create each model. This section will be demonstrated by images, so that the Simulink simulation modelling approach can be determined visually.

This section will only include 2 Degree of Freedom models as the previous section determined that they provide a more realistic interpretation of what is happening. The previous section concludes that the tyre makes a difference to the suspension characteristics.

4.4.1 2 Degree of Freedom Simulink Model

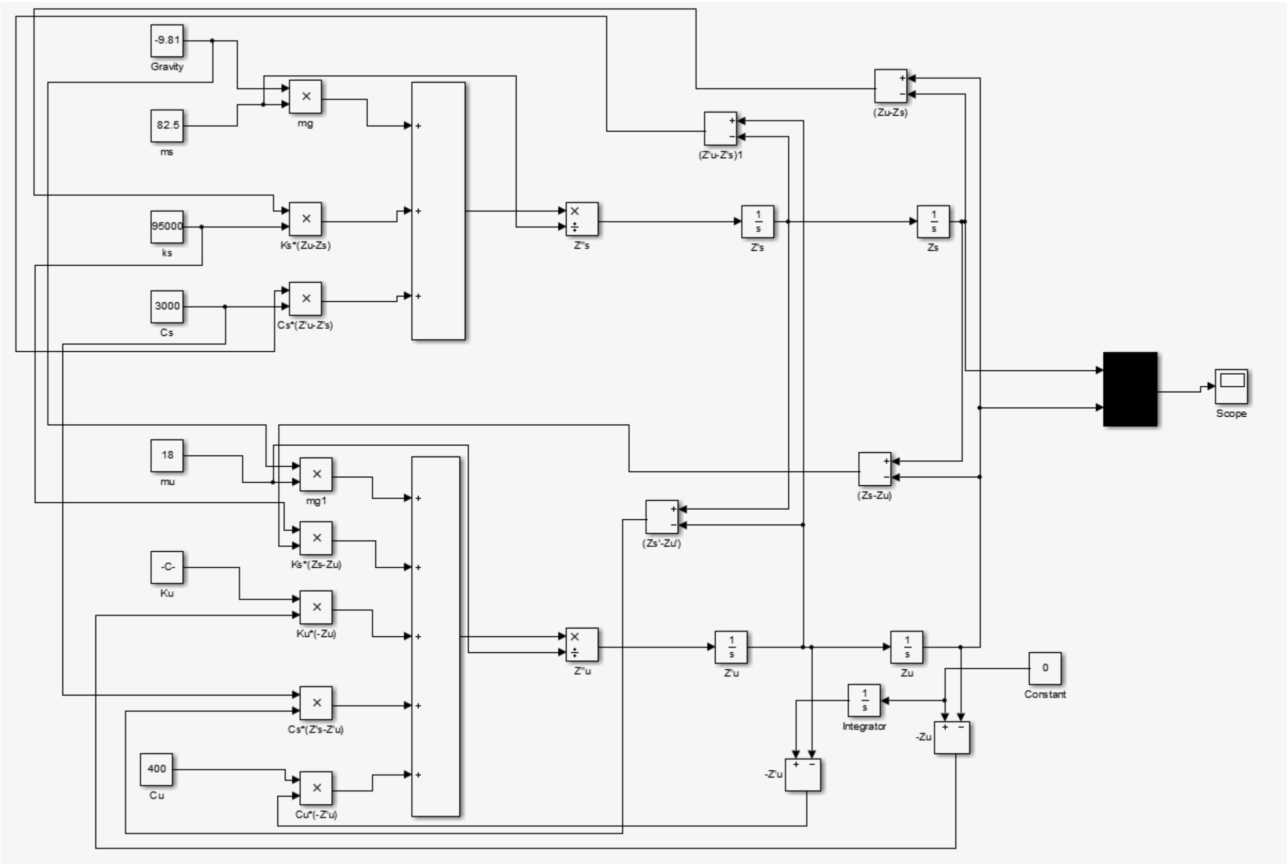

Figure 4-9 - 2 Degree of Freedom Simulink Model

'Figure 4-9' shows how to construct a 2 Degree of Freedom model within Simulink as you can see the 'SAG' has been removed, this is because the model is a static deflection case, where if 'SAG' were to be included, the graph would stay at 0mm displacement. From analysing 'Figure 4-9' it can be seen that the constants from the equations of motion are on the left of the model, and these are then multiplied by the result of each relevant sector, it can be seen that the mass is multiplied with gravity, and then mass is reused after the sum of the products to divide the force into an acceleration of the mass. Each block within the model has been named by either their relevant section within the equation of motion, or the value in which they produce after the block. i.e. Ku*(-Zu) block produces this result of the equation on the output side of the block. By using the scope it is possible to produce the given graphs within the following sections of this thesis.

'Figure 4-10' shows the results of this model with the same time scale of the excel graphs so that graphs can be directly comparable.

'Figure 4-10' gives the similar results to that of 'Figure 4-6'. Therefore, this 2 Degree of Freedom Simulink model has been validated to some extent. The Simulink model has been ran at different time steps, i.e. fixed time steps and variable time steps both with a maximum time step of 1e-9 steps. However the model did not change, it has been simulated using trapezoidal method, equal to that of the Microsoft Excel model, and also with the Euler method. Never the less, the same results are present. The Excel model has used a 0.001s time step which has converged due to, increasing the time step to 0.00025 and 0.0001 provided no changes in the graphs. Both models shows five overshoots on the sprung mass prior to finding equilibrium, it is only the initial displacement of the unsprung mass (Tyre Deflection) which is marginally larger on the Microsoft Excel model. Due to only the small variation in result, it can be established that both models are working well and development to the model can be continued.

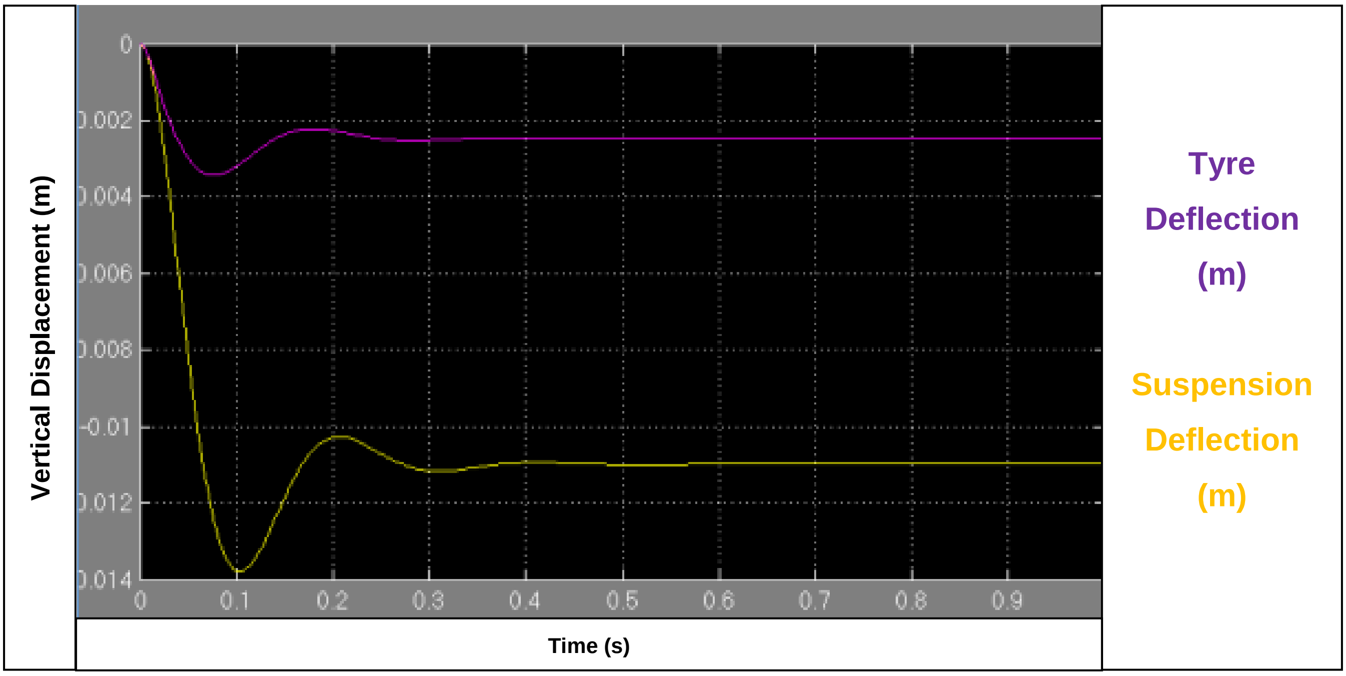

Figure 4-10 - 2 Degree of Freedom Simulink Graph

'Figure 4-11' shows an overlay using Microsoft Paint of the two graphs. It shows the MATALB/Simulink graph in 'Figure 4-10' as the dotted lines and the Microsoft Excel graph in 'Figure 4-6' as the solid lines. It can be seen 'Figure 4-11' that the two graphs follow the same kind of trend with only a small variation. However, MATLAB/Simulink model tends to react slightly quicker, yet still produces the same amount of peeks. Also both models rest and come to equilibrium at a similar point, and essentially showing the same amount of SAG within the vehicle.

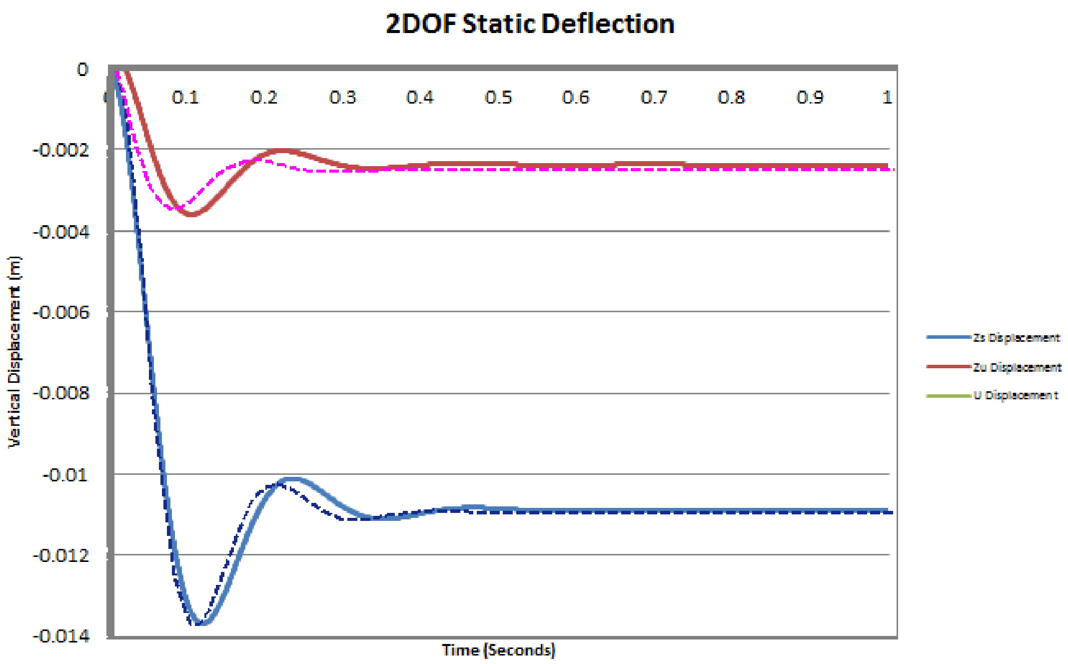

Figure 4-11 - Overlaid Comparison of 'Figure 4-6' and 'Figure 4-10'

4.4.2 2 Degree of Freedom with Step Profile Simulink Model

Using the same process as before the following Simulink model could be created. As you can see in ‘Figure 4-12’ the ‘SAG’ has been re-implemented so that the trend of the suspension and wheel movement follows that of the step profile. This is not essential. However, this allows the user to gain a better interpretation of what the suspension is doing.

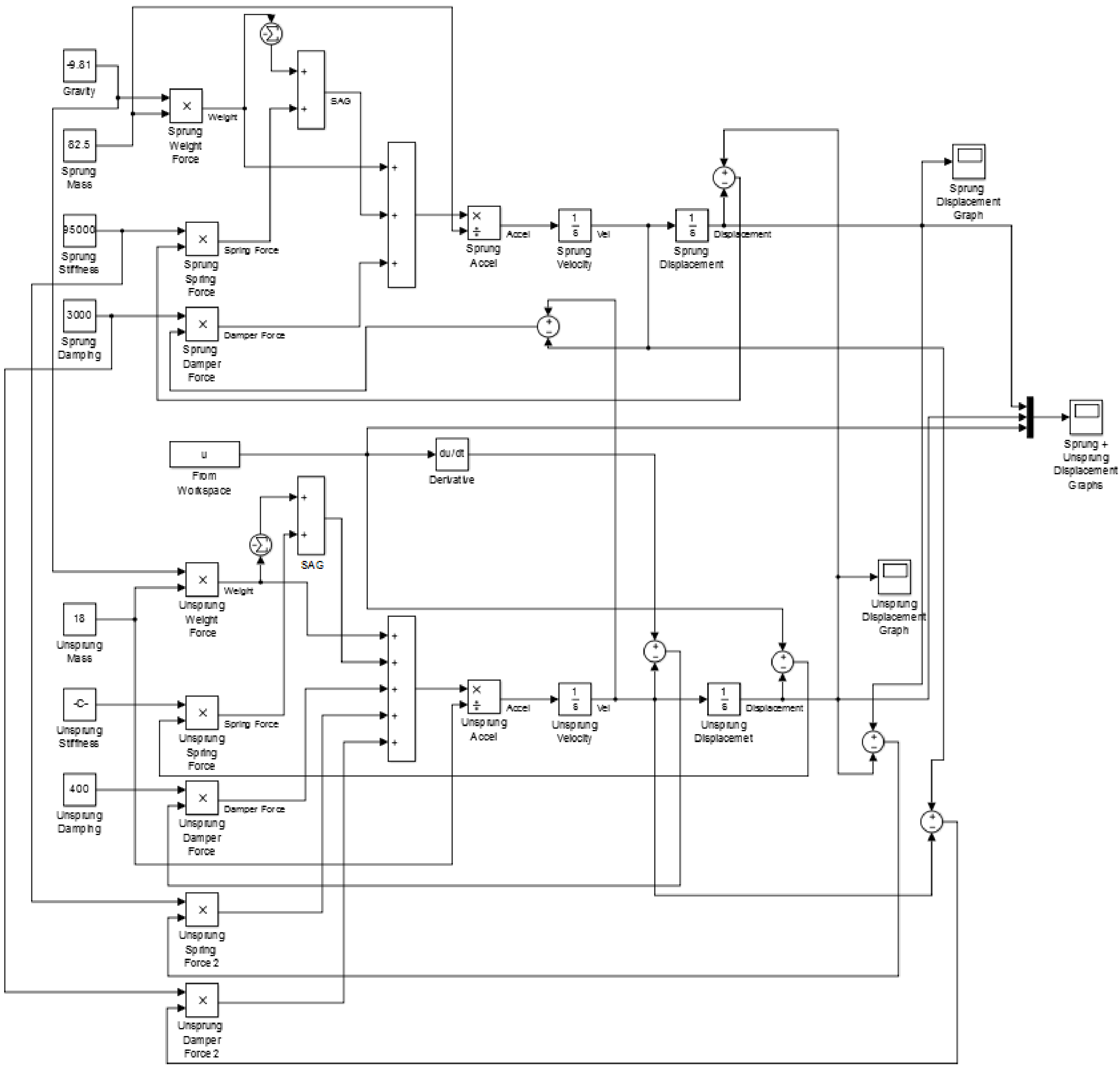

Figure 4-12 - 2 Degree of Freedom with Step Profile Simulink Model

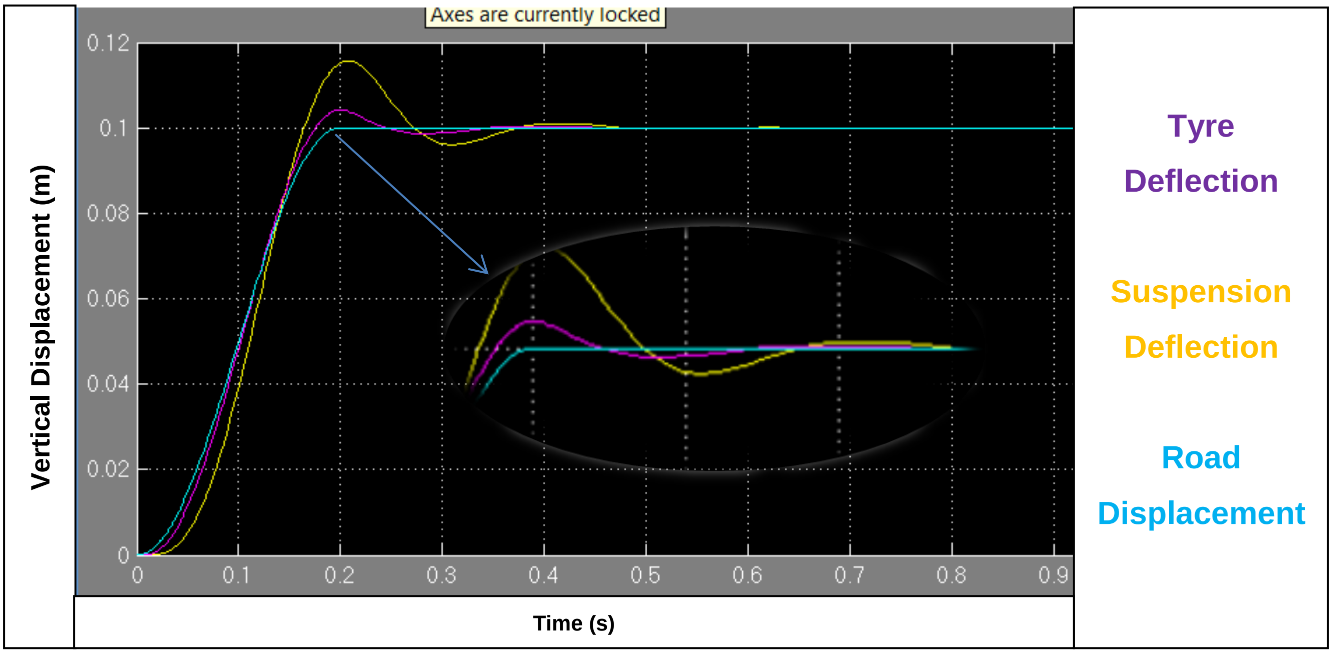

Figure 4-13 - 2 Degree of Freedom with a Step Profile Simulink Graph

'Figure 4-13' shows the suspension movement (Yellow), wheel movement (Purple) and the step profile (Light Blue). The graph shows similar results of that in Microsoft Excel, yet the variation is the same of that of the previous 2DOF system created, shown in 'Figure 4-9'. Therefore the study can now progress to adjust only the sprung damping characteristics to determine their effects on the system.

4.5 Damping Adjustments

Within this section of the report, the damping characteristics of the suspension will be adjusted, it will be performed in the process of a large increment in both directions to establish the major effects of 'firm' and 'soft' suspension.

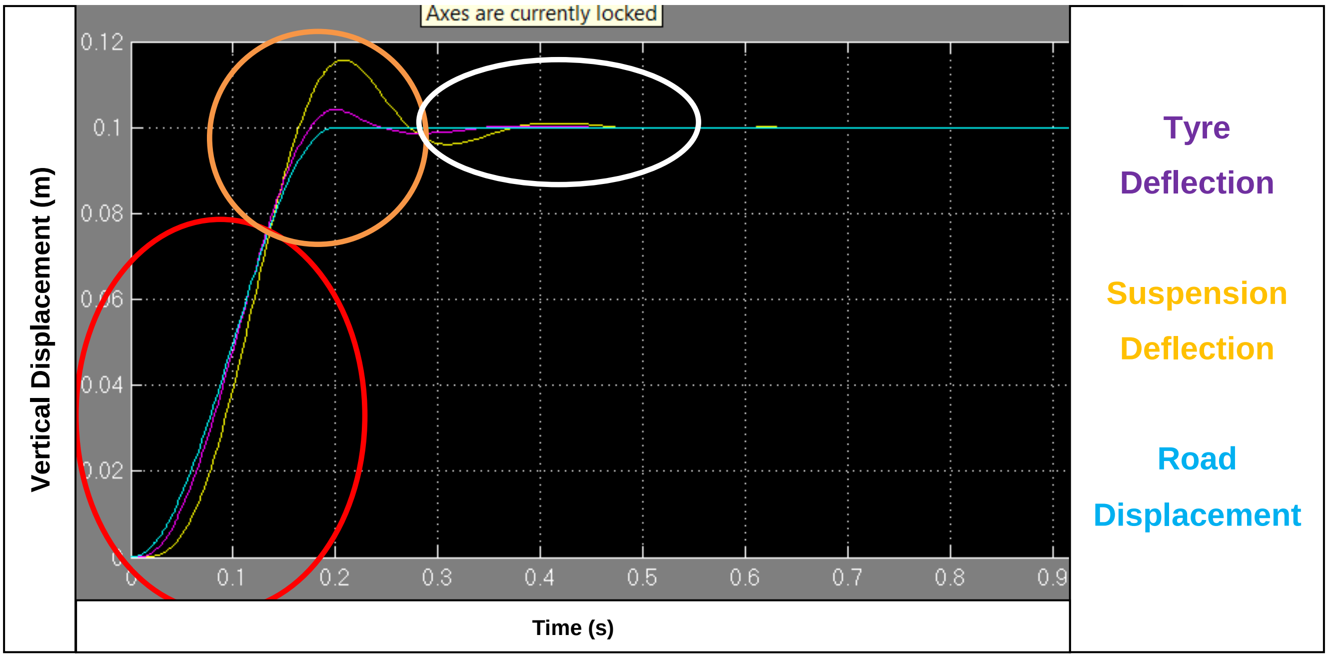

Figure 4-14 - Division of the Step

The study will make large increments of 1,000Ns/m, followed by closer increments of 500 Ns/m to determine an ideal damping coefficient for the given parameters. The study will look into the effects of damping adjustments for each section of the step. I.E. the step will be split into three sections. ‘Figure 4-14’ shows each section of the step to be studied, and can be identified as section 1 (Red), section 2 (Orange) and section 3 (White)

It can now be stated that ideal suspension keeps the tyre in contact with the road at all times. Therefore, by being able to manipulate the damping of the suspension we should be able to ensure that the wheel displacement trend stays along the line, or as close to, that of the step displacement plot (Light Blue). The ‘Base Line Graph’ Shown in ‘Figure 4-13’ suggests that the system could be relatively under-damped.

4.5.1.1 ‘Firmer’

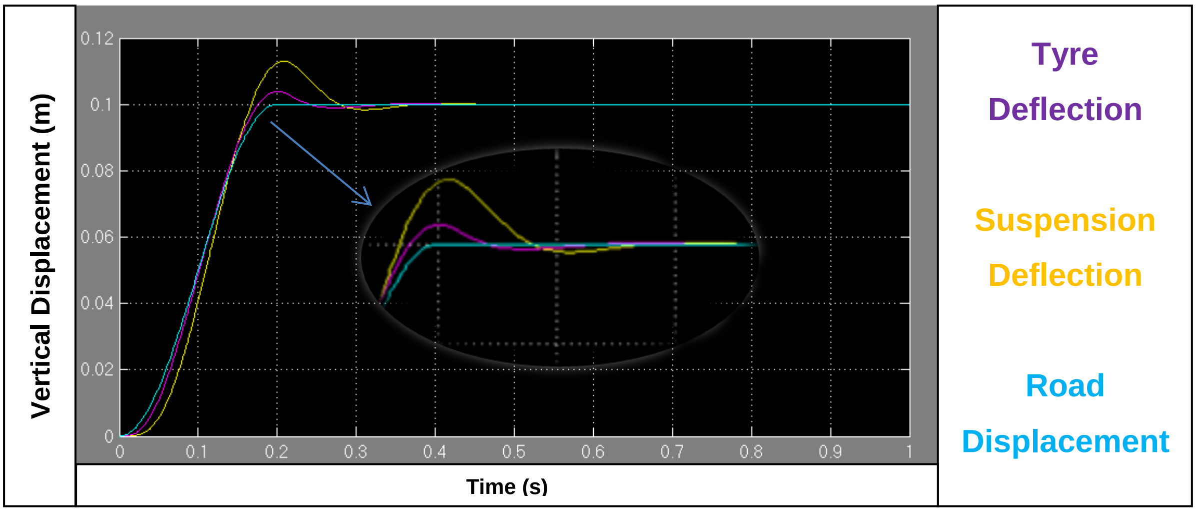

Figure 4-15 – 4,000 Ns/m Damping Factor

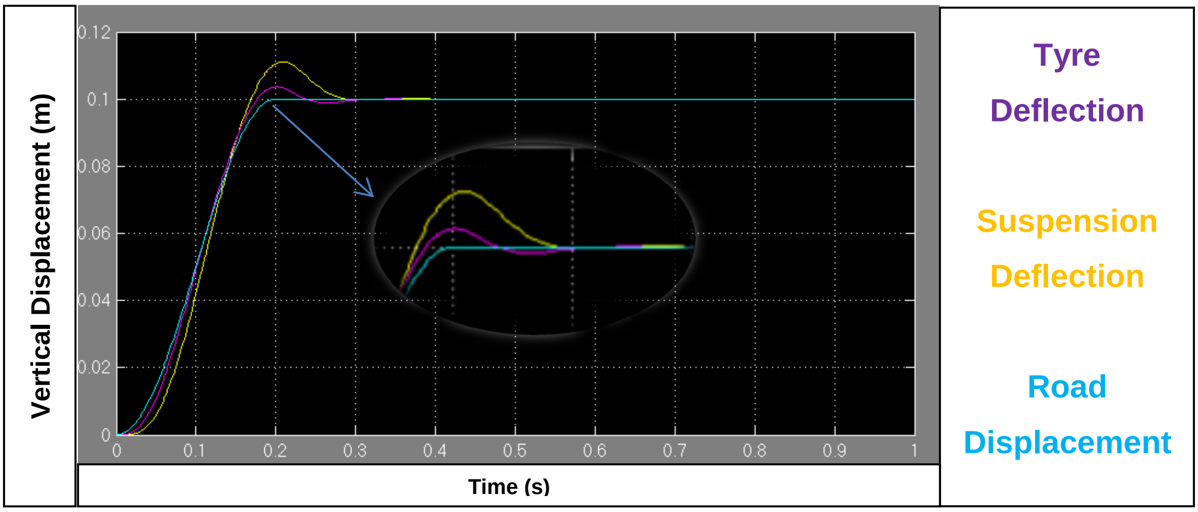

Figure 4-16 – 5,000 Ns/m Damping Factor

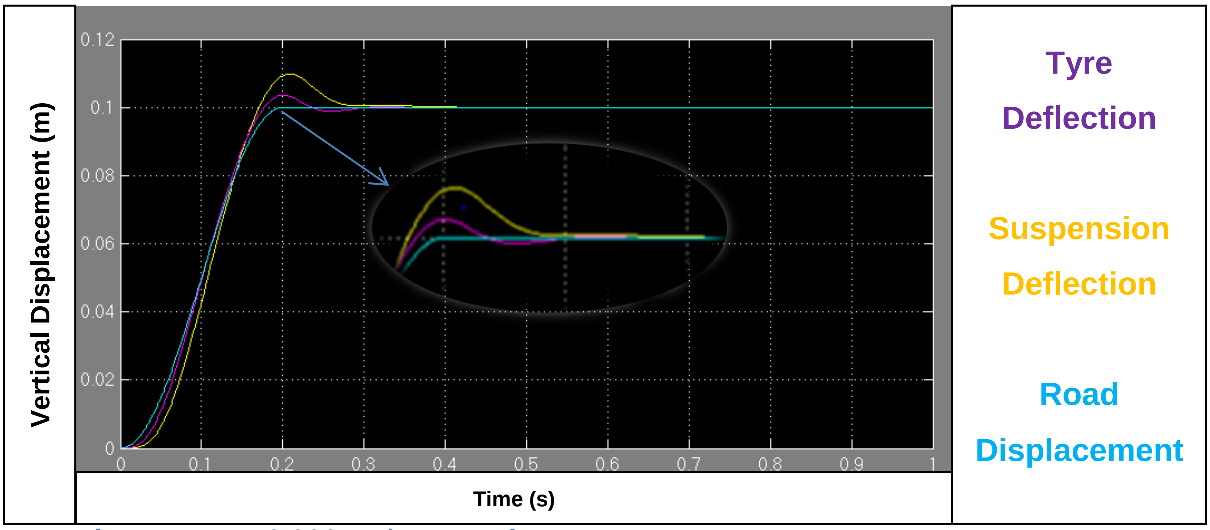

Figure 4-17 – 6,000 Ns/m Damping Factor

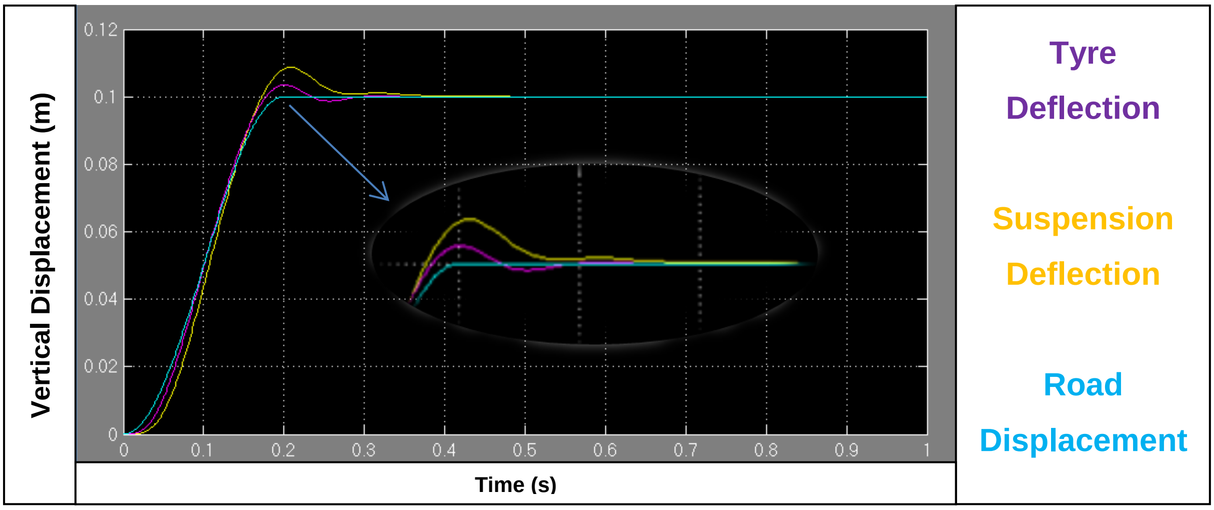

Figure 4-18 – 7,000 Ns/m Damping Factor

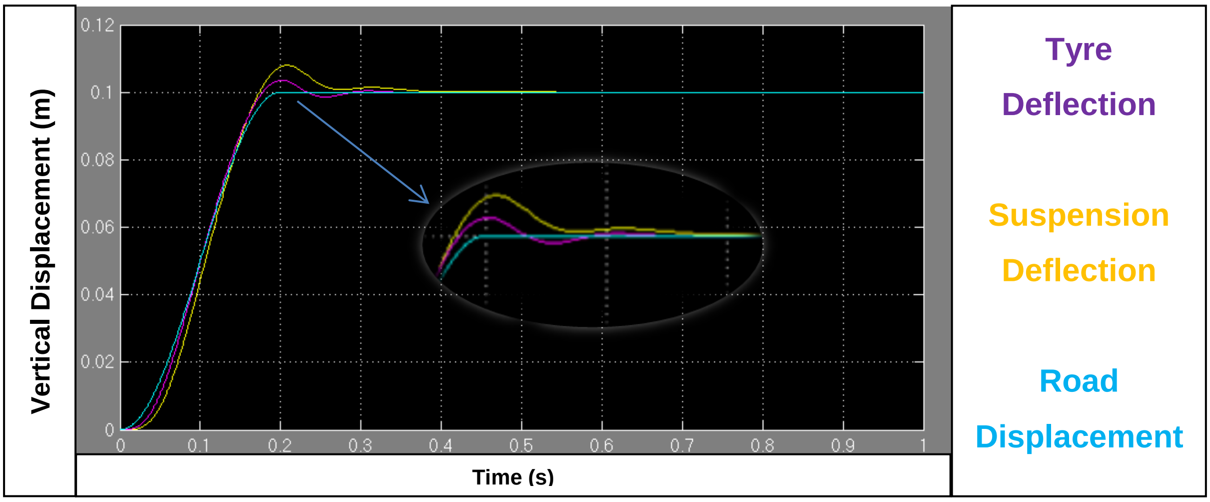

Figure 4-19 – 8,000 Ns/m Damping Factor

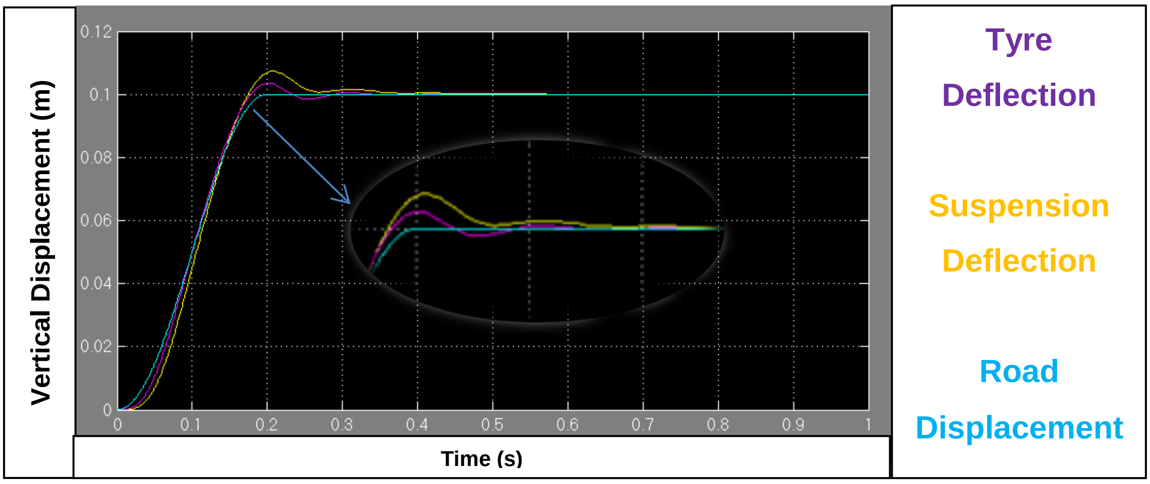

Figure 4-20 – 9,000 Ns/m Damping Factor

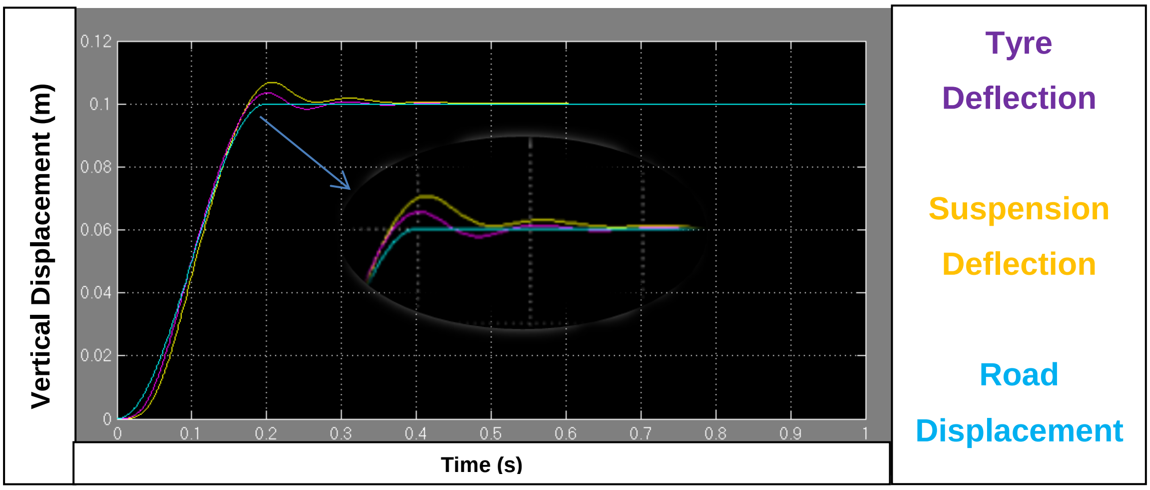

Figure 4-21 – 10,000 Ns/m Damping Factor

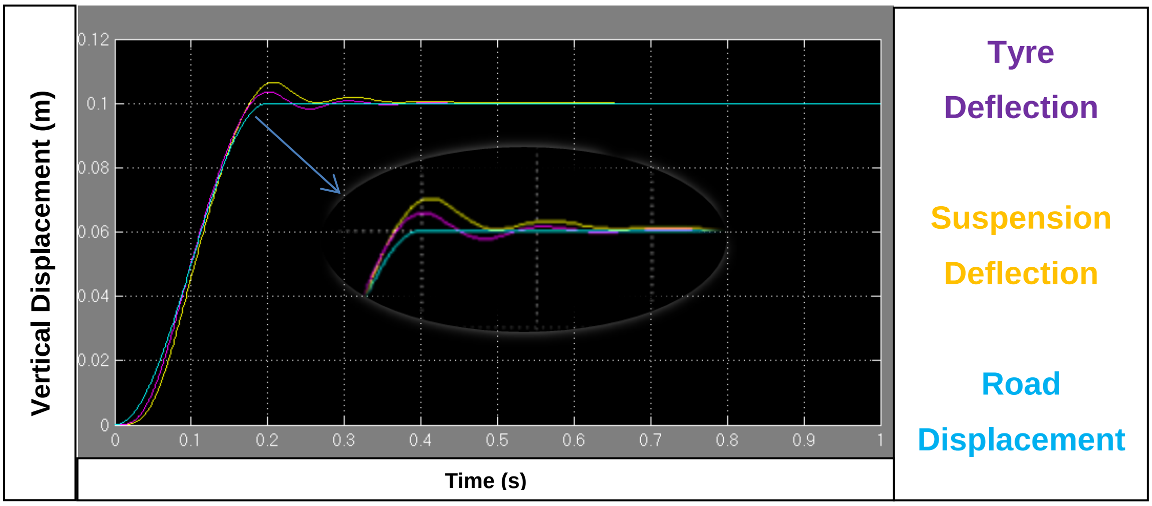

Figure 4-22 – 11,000 Ns/m Damping Factor

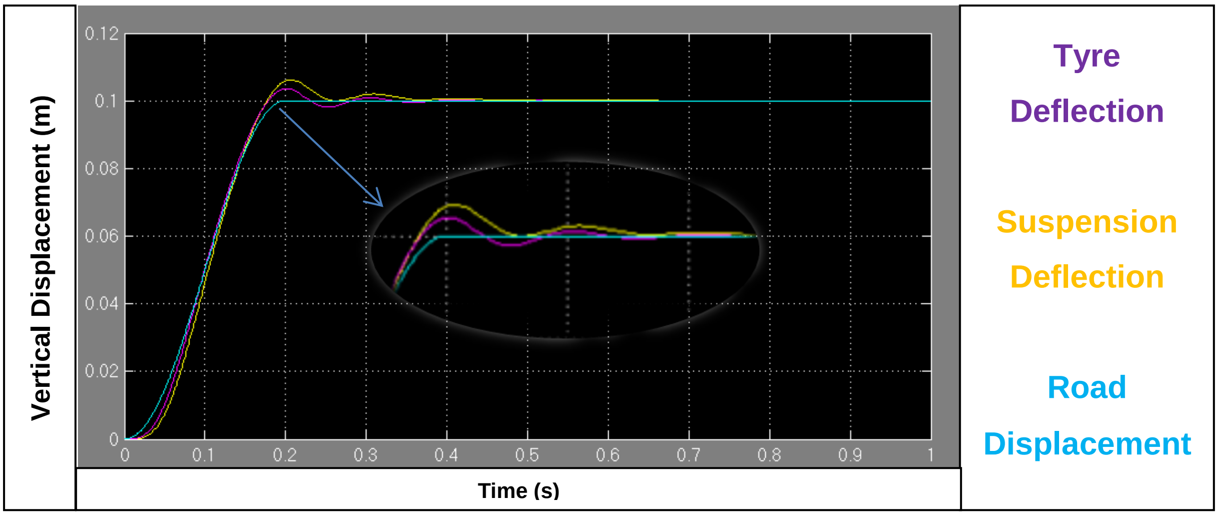

Figure 4-23 – 12,000 Ns/m Damping Factor

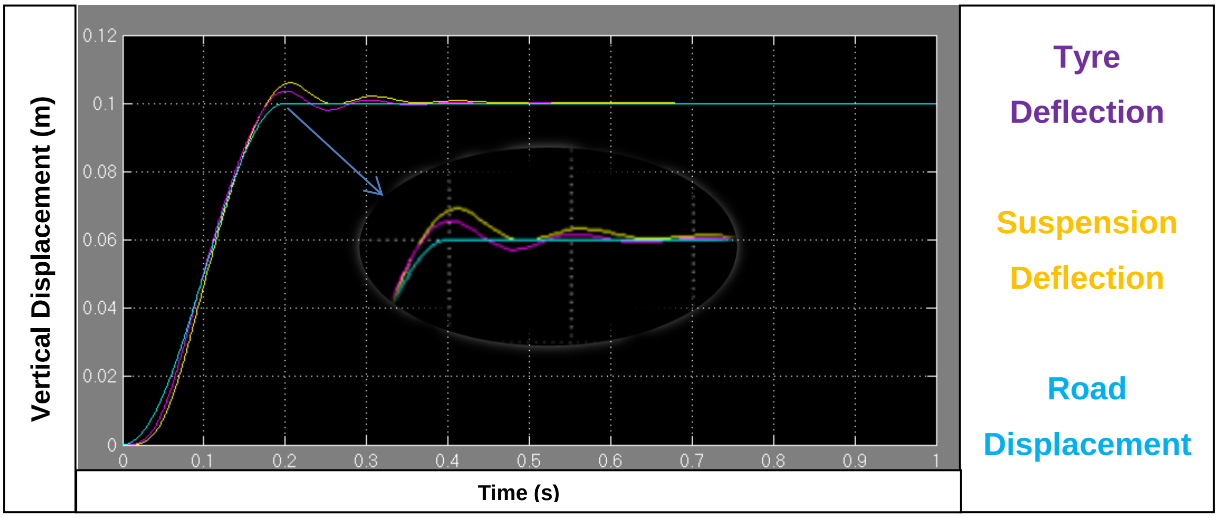

Figure 4-24 – 13,000 Ns/m Damping Factor

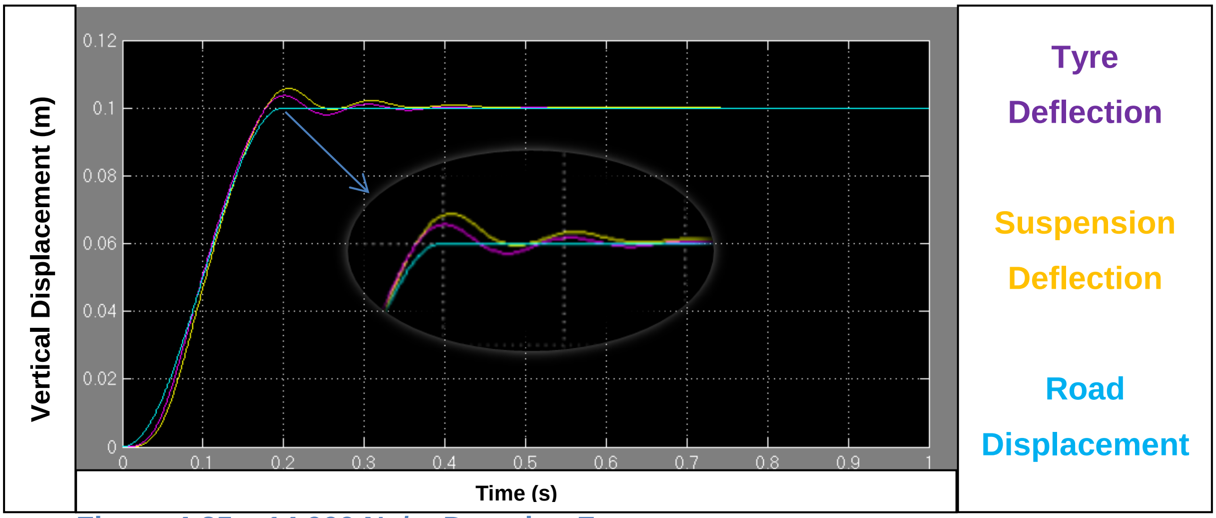

Figure 4-25 – 14,000 Ns/m Damping Factor

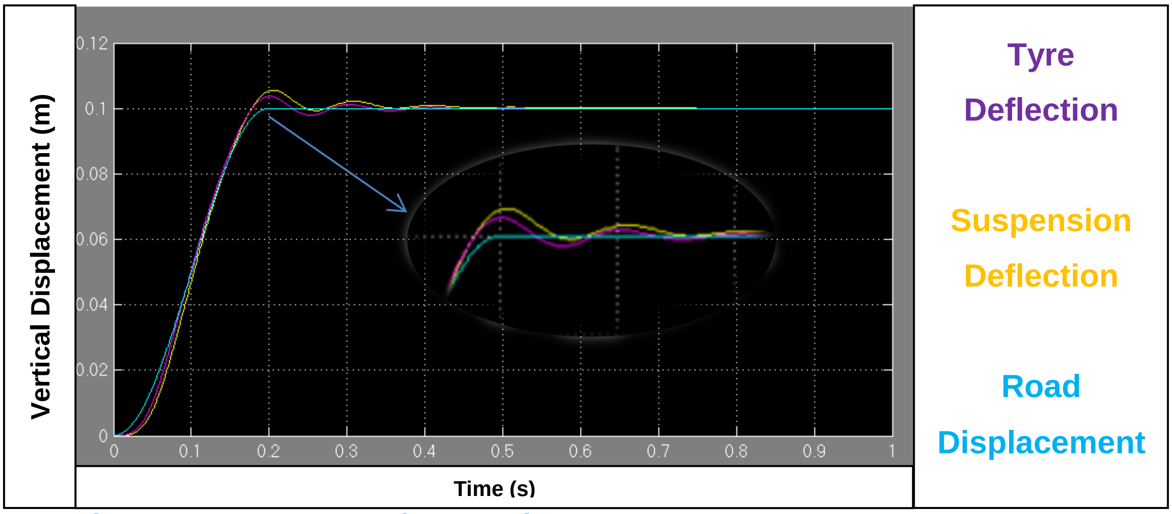

Figure 4-26 – 15,000 Ns/m Damping Factor

From the graphs within this section, it can be seen that when the damping is increased the suspension displacement trend moves closer to that of the wheel displacement. Therefore, the tyre is still losing contact with the ground within this section. However, the maximum suspension displacement has been reduced by approximately 10mm from 3,000Ns/m of damping to 15,000Ns/m of damping. The oscillations actually start to increase when the vehicle is over damped, this can be seen from 'Figure 4-23' to 'Figure 4-26', which could be that the suspension forces the tyre closer to its natural frequency causing the increase in oscillations, and finally section '4.5.1.1 'Firmer'' shows only a small change in initial displacement (section 1 of the graph) when the damping has been increased. However, this effect is only in the suspension displacement and not in the tyre displacement.

4.5.1.2 'Softer'

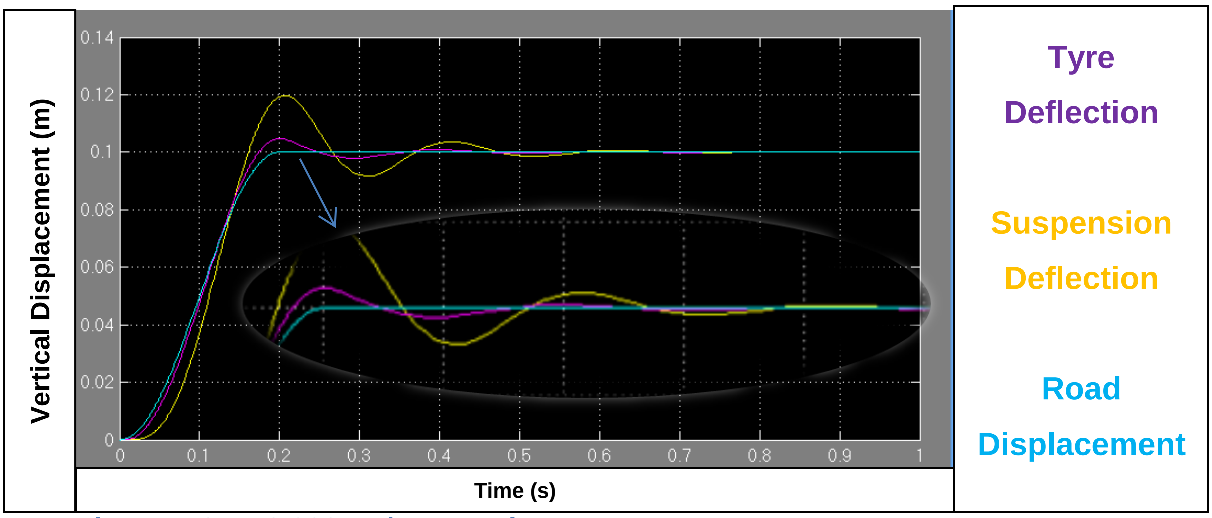

Figure 4-27 – 2,000 Ns/m Damping Factor

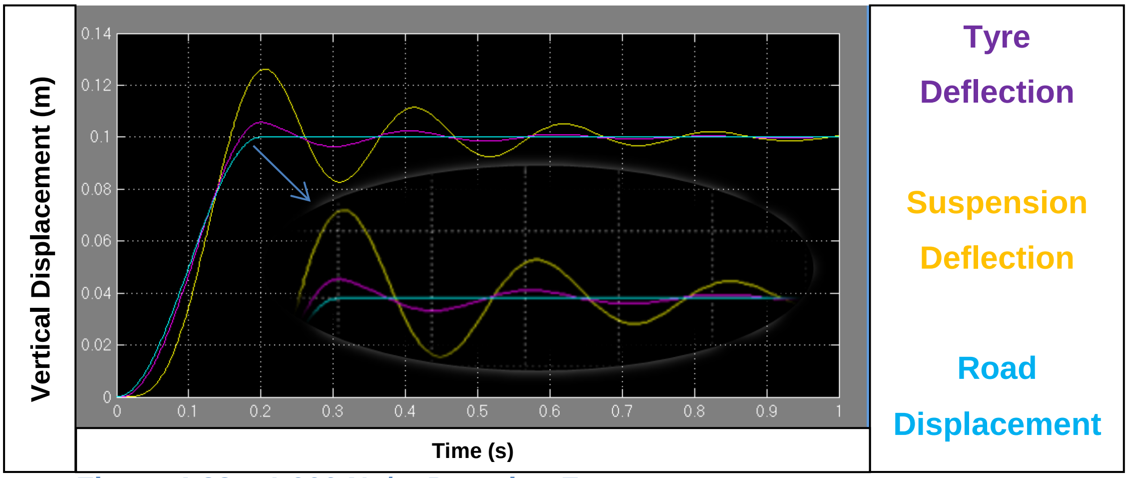

Figure 4-28 – 1,000 Ns/m Damping Factor

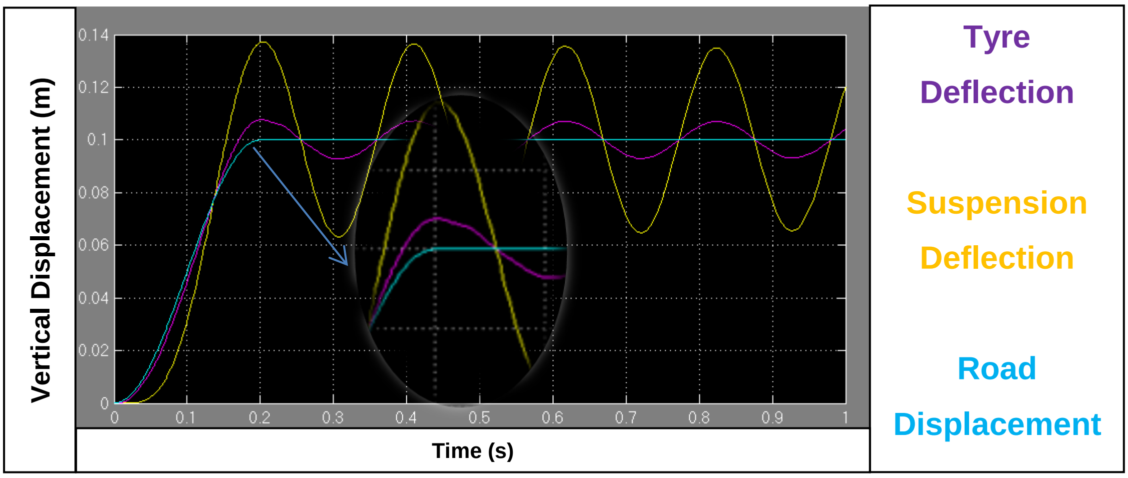

Figure 4-29 - 0 Ns/m Damping Factor

From reducing the damping, it can be seen within the graphs, that there is a significant increase in both suspension displacement and tyre displacement. Therefore, as the suspension gets 'softer' the oscillations increase. However, the largest suspension peak does not increase past 28mm. The initial tyre peak doesn't change throughout the adjustments until there is no damping present. The initial suspension displacement has increased and shows a longer delay before reacting to the step: by reducing the damping; section 1 of the tyre has not been affected. Therefore, it can be assumed that these are characteristics of the tyre, and cannot be affected by suspension damping characteristics. Section 2 shows that when the damping is reduced the wheel loses contact with the step at an earlier point in time; giving the tyre a longer 'time-in-flight' and resulting in the tyre to oscillate more through to section 3 of the graph. From the oscillation of the tyre we can assume that the forces acting on the tyre are changing more often which will increase tyre wear. By reducing this excessive tyre wear, grip could be improved. 'Figure 4-29' States that if the system is given no damping that excessive tyre wear would be present and create an uncontrollable ride.

4.5.1.3 Fine Damping

It can now be stated that the earlier assumption was incorrect. The current damping of the vehicle is fairly well damped for the given system (in comparison to the previous 'softer' results). However, developments can still be made. For example, if the damping is doubled then the overshoot for the tyre and the suspension is reduced. However, if the damping is tripled the tyre forces are increased, but reduces the time in which is takes to reach equilibrium. Therefore, it can be stated that the system needs to be 'Firmer' and have a damping value above 3,000 Ns/m.

Consequently, adjustments of 500Ns/m will be performed in making the suspension 'Firmer' from a value of 2,000Ns/m, whilst overlaying the original 3000 Nm/s damping graph.

As Mathworks Matlab Simulink does not provide a legend tool in the scope output; Therefore, the graph can be analysed as followed; the original suspension displacement (Red) and original wheel displacement (Green). The modified suspension displacement (Yellow) and modified wheel displacement (Purple). The road displacement (Light Blue).

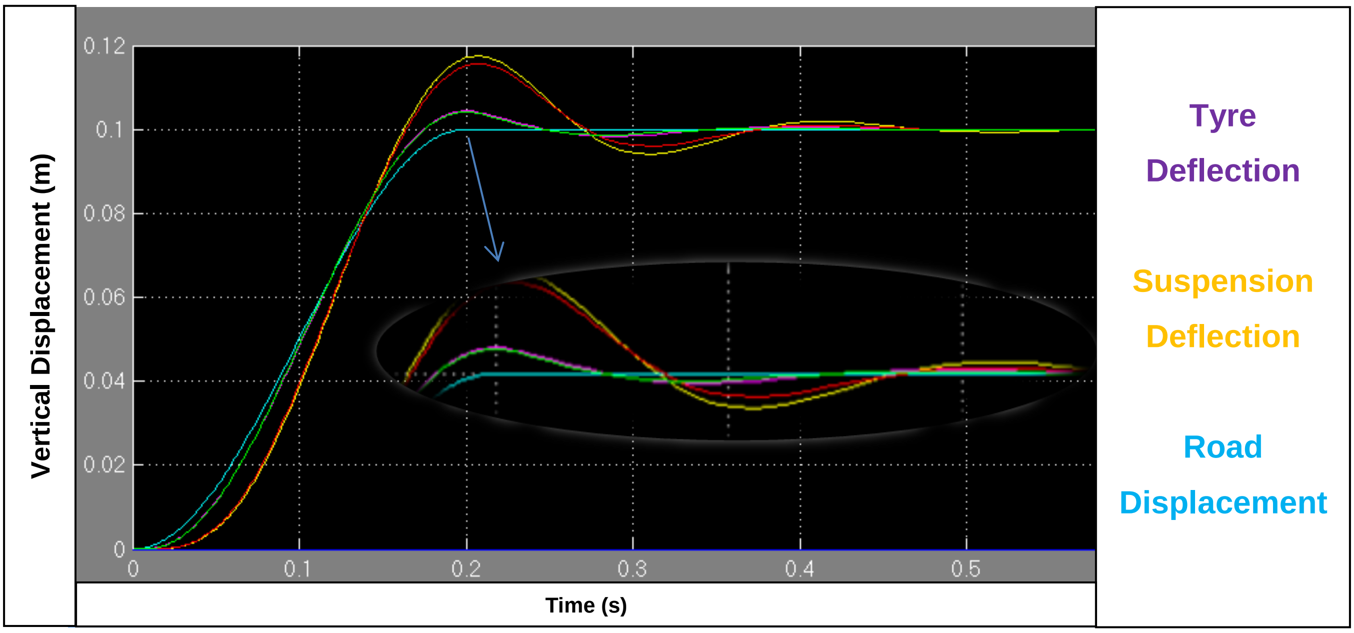

Figure 4-30 – 2,500 Ns/m Damping Factor

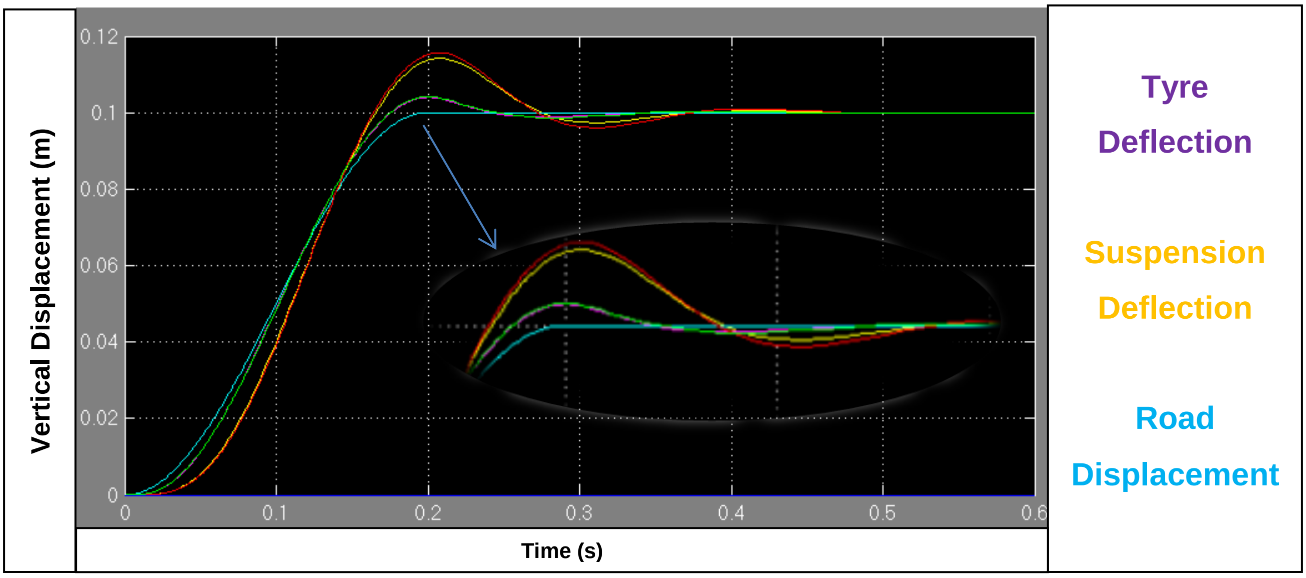

Figure 4-31 – 3,500 Ns/m Damping Factor

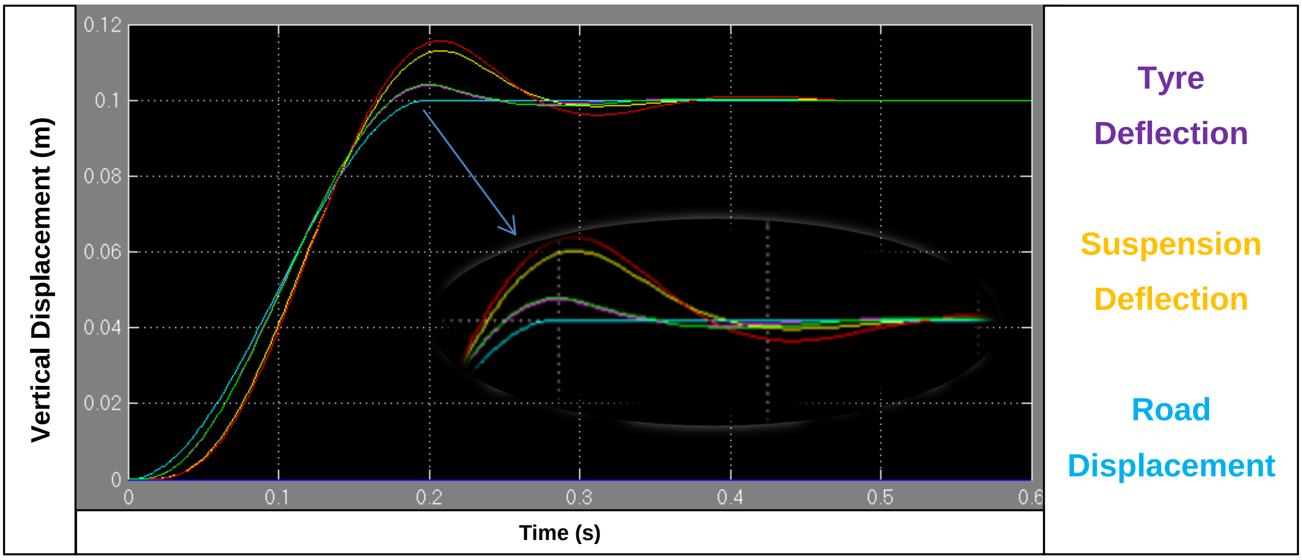

Figure 4-32 – 4,000 Ns/m Damping Factor

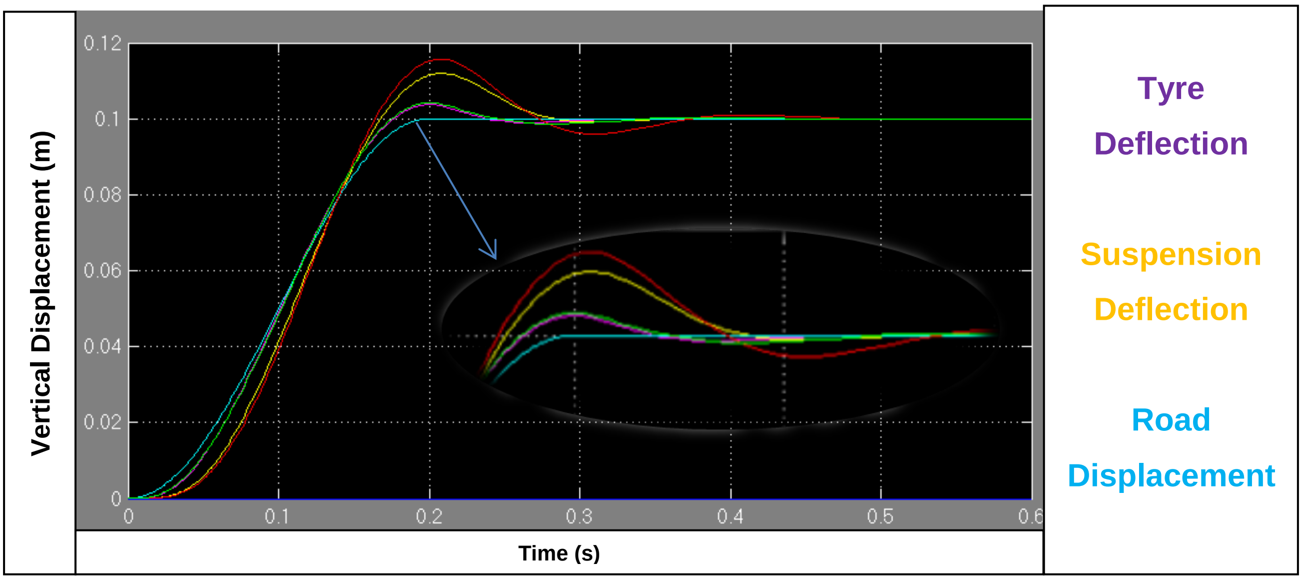

Figure 4-33 – 4,500 Ns/m Damping Factor

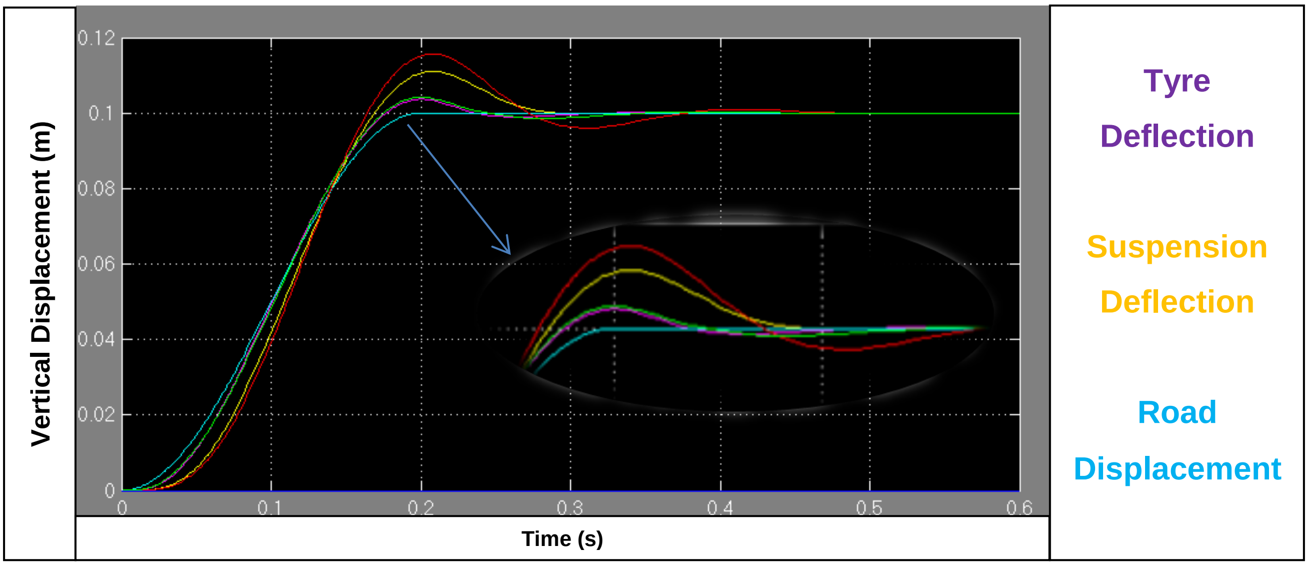

Figure 4-34 – 5,000 Ns/m Damping Factor

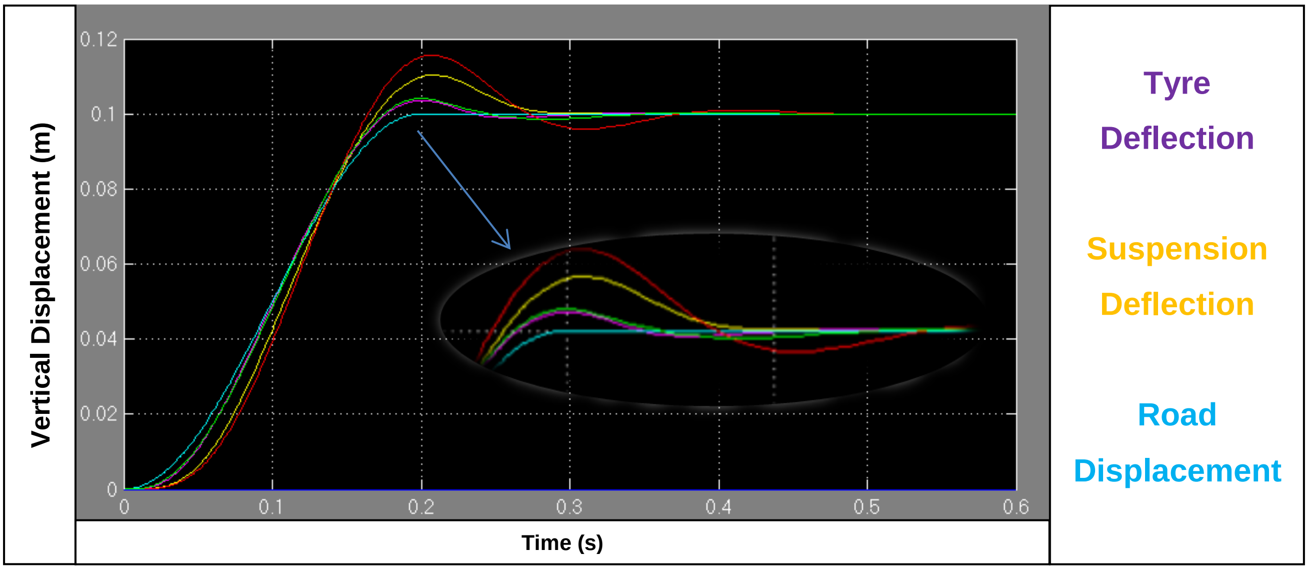

Figure 4-35 – 5,500 Ns/m Damping Factor

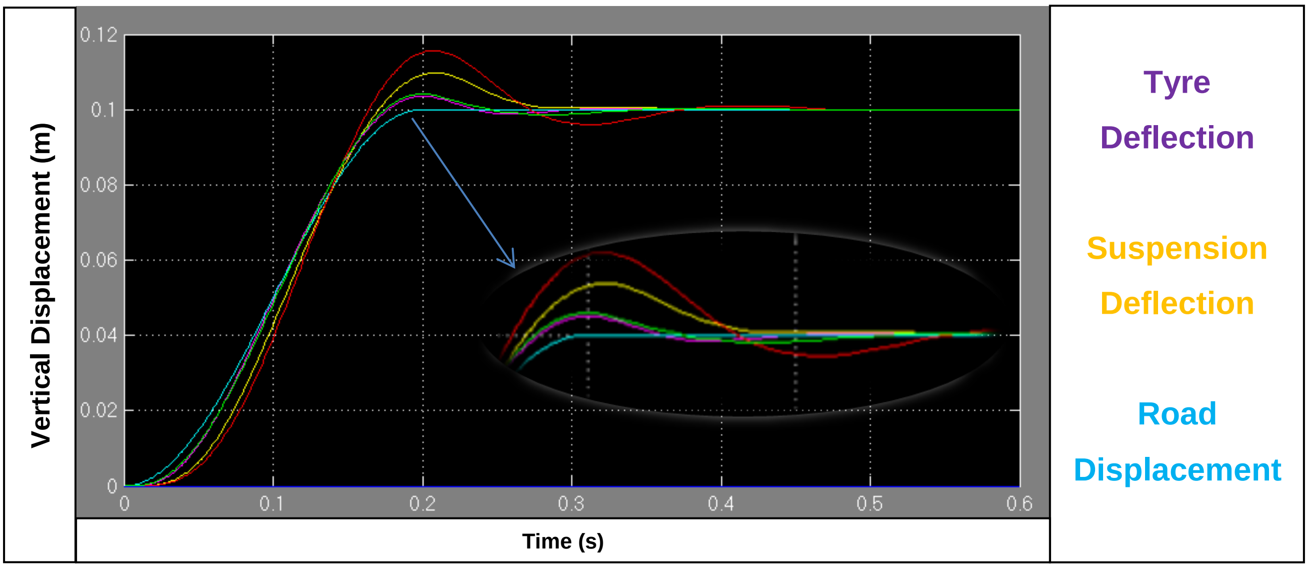

Figure 4-36 – 6,000 Ns/m Damping Factor

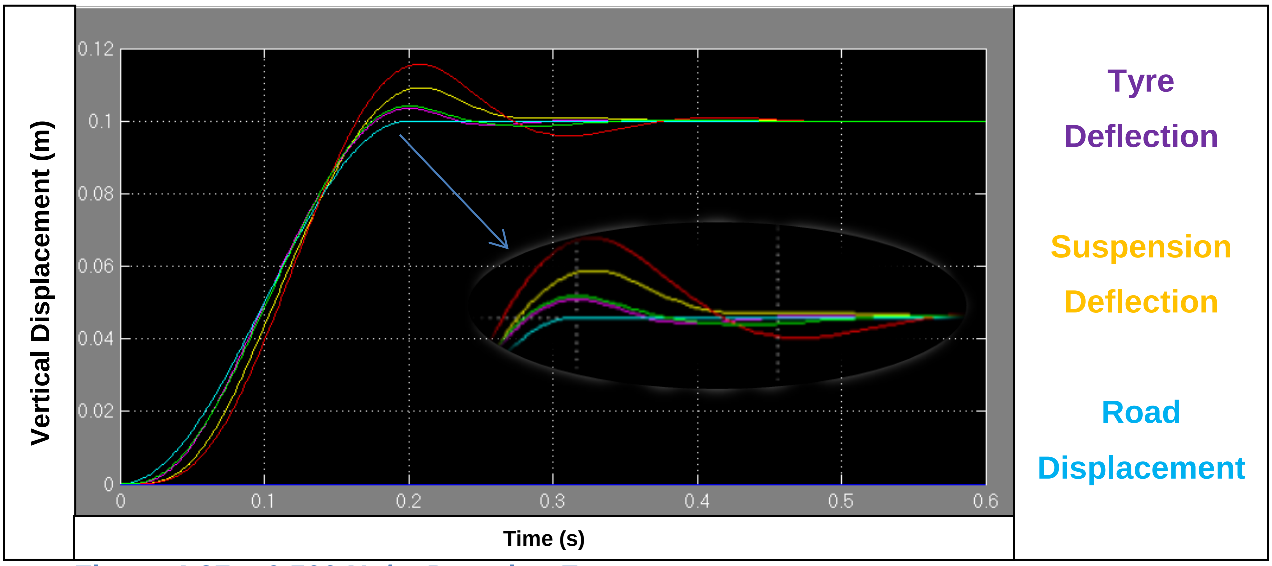

Figure 4-37 - 6,500 Ns/m Damping Factor

From ‘Figure 4-33’ it can be seen, that the modified suspension displacement (Yellow) has been reduces to minimal secondary overshoot, suggesting that the system is critically damped with a ride damping ratio of just below 1. The graph also shows that only 8mm of travel would be used in this scenario which would cause a larger force transferring to the rider. However, this is only two thirds the displacement which was occurring at 3,000Ns/m of damping; if a smoother ride was required then lower spring stiffness’s would be suggested. Considering, this study is proposed for motorsport intentions; the stiffer spring is required for braking case scenarios. ‘Figure 4-33’ also states that the tyre still has a secondary overshoot. Therefore, to optimise the grip it would be recommended that a damping ratio of 1 would need to be achieved.

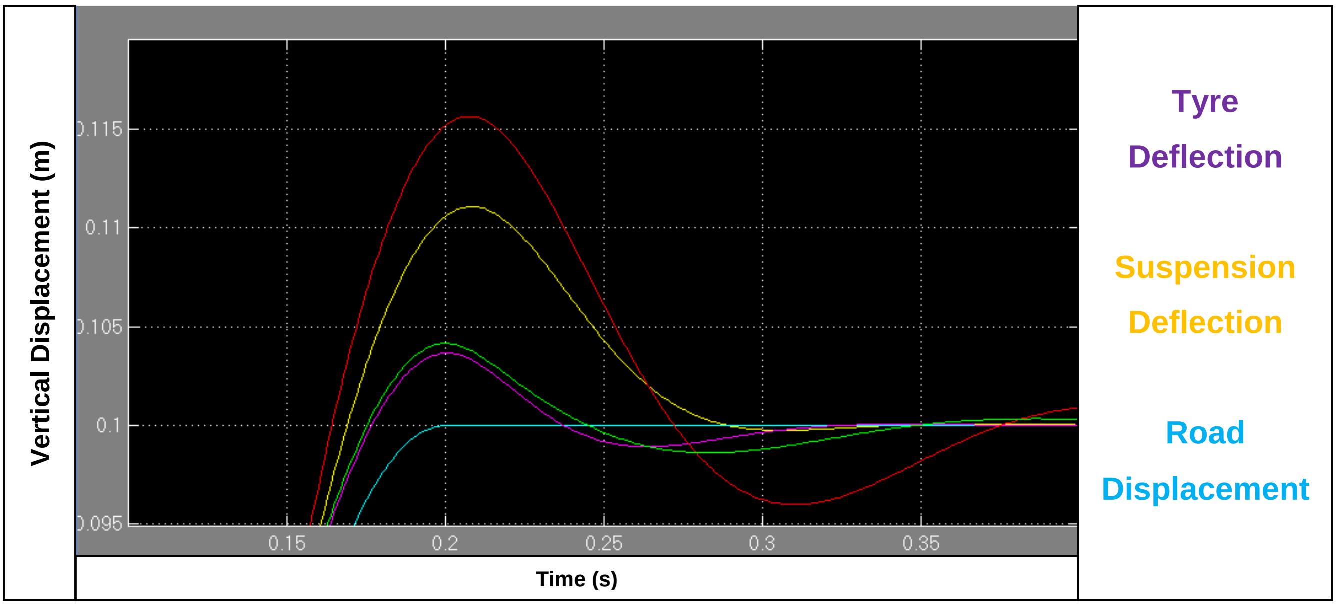

Figure 4-38 - Close Up 6,000 Ns/m Damping Factor

From ‘Figure 4-38’ it can be seen that the wheel and suspension displacements follow that of the step profile closer with the given 6,000 Ns/m of damping; 6,000 Ns/m of damping provides a 1.08 Damping Ratio. The graph also states that the wheel returns to equilibrium sooner, giving the rider more control of the vehicle within a shorter period of time.

4.5.1.4 Calculating the Ride Damping Ratio

Equation 4-29

$$\boldsymbol{\delta} = \frac{c_s}{2 * \sqrt{\left(\frac{1}{\frac{1}{k_s} + \frac{1}{k_u}}\right) * (m_s + m_u)}}$$

$$\boldsymbol{\delta} = \frac{6000}{2 * \sqrt{\left(\frac{1}{\frac{1}{95000} + \frac{1}{400000}}\right) * (82.5 + 18)}}$$

$$\boldsymbol{\delta} = \frac{6000}{2 * \sqrt{76767.67677 * 100.5}} = 1.08$$

4.5.1.5 Calculating the Ride Natural Frequency

Equation 4-30

$$\boldsymbol{f_n} = \frac{\sqrt{\frac{\left(\frac{1}{\frac{1}{k_s} + \frac{1}{k_u}}\right)}{(m_s + m_u)}}}{(2 * \pi)}$$

$$\boldsymbol{f_n} = \frac{\sqrt{\frac{76767.67677}{100.5}}}{6.283185307}$$

$$\boldsymbol{f_n} = 4.398\ [\boldsymbol{hz}]$$

4.6 Increasing Speed

This section of the study will look into the effects of grip when increasing the speed of the vehicle. It is a well-known fact the motorsport racers will change their suspension multiple times within a race weekend. This study will determine if there is a correct suspension setting per vehicle or if suspension needs to be adjusted dependant on vehicle speed in order to maintain grip. The study will use the Microsoft Excel models in order to determine ‘Grip Index’, ‘Heave Comfort’ and ‘Pitch Comfort’. ISO2631 (International Standard, 2009) gives a discomfort threshold of $5m/s^2$ for 1 hour exposure at 1-2 Hz. Therefore, for the given Heave and Pitch comfort indexes, $5m/s^2$ will be used. The indexes will refer to 0 as poor, when the value is increased the areas can be determined as improved i.e. 10+ would be an optimum. The method in which the speed will be increase, will be a reduction in the step duration, this will provide an increase in speed. It can be stated that a physical speed unit, i.e. KPH, MPH or m/s, is not required as that would depend on the step length, it is clear that if the step was 1m long it would be traveling faster than if the step was only 0.5m long. The vehicle would travel a longer distance prior to returning to the ground with a longer step length. However, the vehicle would still react in the same manor, in reference to time. Therefore, by only decreasing the step duration and referring to it as a percentage increase in speed, an adequate study can still be performed.

4.6.1 Calculating Simplified Grip Index

Equation 4-31

$$\boldsymbol{Average\ Tyre\ Force}\ [\boldsymbol{N}] = Average\big(K_u(U - Z_u) + C_u(\dot{U} - \dot{Z}_u) + K_s(Z_u - Z_s) + C_s(\dot{Z}_u - \dot{Z}_s) + (m_{ug} * -g)\big)$$

Equation 4-32

$$\boldsymbol{Tyre\ Force} - \boldsymbol{Average\ Tyre\ Force}\ [\boldsymbol{N}] = \big[\{K_u(U - Z_u) + C_u(\dot{U} - \dot{Z}_u) + K_s(Z_u - Z_s) + C_s(\dot{Z}_u - \dot{Z}_s) + (m_{ug} * -g)\} - Average\ Tyre\ Force\big]^2$$

Equation 4-33

$$\boldsymbol{Average\ Tyre\ Force2}\ = \sqrt{Average(Tyre\ Force - Average\ Tyre\ Force)}$$

Equation 4-34

$$\boldsymbol{Tyre2} = \frac{Average\ Tyre\ Force2}{1000}$$

Equation 4-35

$$\boldsymbol{Grip\ Index} = \frac{1}{Tyre2}$$

The given Grip Index, has been developed from the principles found in (Anderson & Harty, 2013), (Li, et al., 2011), (Fleury & Mistrot, 2006), (Zegelaar, 1998) and (Harty, 2009). All these authors use a performance indicator, which work on the same principle of taking the RMS, of the average forces or accelerations. The given grip index, most commonly represents that of which was used in Anderson & Harty's work, named as the KPI Comfort index. However, where Anderson & Harty used the accelerations of the body and tyre, this equation has only used the forces at the tyre in order to generate the given index. This equation works as the tyre forces are not always equal within the tyre because the tyre contains damping properties. Thus, allowing for the tyre to come to rest and the forces to decay. Due to the decaying forces in the tyre, the average tyre force can never dynamically be equal to 0. Therefore, by taking the average of this and then the RMS, a singular number can be generated which represents an index similar to that of the Cooper scale just much larger. The result is then divided by 1000 to scale it down to a sensible number. The reciprocal of this scaled number is used to generate the given KPI Grip index within this thesis. The limitation of this index is that, it is only directly comparable against simulations done of the same duration. This is because, it averages the entire simulation. Therefore, if the simulation was extended for a different road profile i.e. a

5s study compared to a 10s study. The results would not compare as the vehicle could come to rest at 8s instead of 9s, thus, not allowing the 5s study to average to rest period. All comparative studies should be completed with the same simulation time and integration, for the grip index to have the correct comparative results. For example, if a step profile of 0.1m in height, a duration of 0.04s is used with a simulation duration of 5s the Grip Index produces a result of 5.1. However, if we keep everything else the same and only increase the simulation time to 10s i.e. increase the resting period by a further 5s, it increases the Grip index by 5.09, a result of 10.19. This is due to the fact that the vehicle has reached equilibrium after traveling over the step at simulation time 0.7s. The result of this is that, the further 4.3s (for the 5s simulation) and 9.3s (for the 10s simulation) are solely improving the grip index as the tyre is stationary and the forces acting through the tyre are no longer varying.

4.6.2 Calculating Simplified Heave Comfort

Equation 4-36

$$\boldsymbol{Average\ \ddot{Z}_t[m/s^2]} = Average(\ddot{Z}_t)$$

Equation 4-37

$$\boldsymbol{\ddot{Z}_t - Average\ Z_t[\ddot{m}/s^2]} = \{\ddot{Z}_t - \ Average(\ddot{Z}_t)\}^2$$

Equation 4-38

$$\boldsymbol{Average\ 2\ \ddot{Z}_t} = \sqrt{Average(\ddot{Z}_t - Average\ \ddot{Z}_t)}$$

Equation 4-39

$$\boldsymbol{Heave\_Comfort2} = \frac{1}{Average\ 2\ \ddot{Z}_t}$$

Equation 4-40

$$\boldsymbol{Heave\ Comfort} = 5 - Heave\_Comfort2$$

The given Heave Comfort index is based on the Anderson & Harty Comfort KPI (Anderson & Harty, 2013) Which can be seen in 'Figure 3-1'. However, this heave Comfort index works on the theory of a maximum vertical acceleration threshold of 5m/s^2 for 1 hour exposure. The index works in the same way as the previous Grip Index in section '4.6.1 - Calculating Simplified Grip Index'.

4.6.3 Calculating Simplified Pitch Comfort

Equation 4-41

$$\boldsymbol{Average\ \ddot{\theta}_t[deg/s^2]} = Average(\ddot{\theta}_t)$$

Equation 4-42

$$\boldsymbol{\ddot{\theta}_t - Average\ \ddot{\theta}_t[deg/s^2]}\ = \{\ddot{\theta}_t - \ Average(\ddot{\theta}_t)\}^2$$

Equation 4-43

$$\boldsymbol{Average\ 2\ \ddot{\theta}_t} = \sqrt{Average(\ddot{\theta}_t - Average\ \ddot{\theta}_t)}$$

Equation 4-44

$$\boldsymbol{Pitch\_Comfort2} = \frac{1}{Average\ 2\ \ddot{\theta}_t}$$

Equation 4-45

$$\boldsymbol{Pitch\ Comfort} = 5 - Pitch\_Comfort2$$

The given Pitch Comfort index is based on the Anderson & Harty Comfort KPI (Anderson & Harty, 2013) Which can be seen in 'Figure 3-1'. However, this Pitch Comfort index works on the theory of a maximum angular acceleration threshold of 5deg/s^2 for 1 hour exposure. The index works in the same way as the previous Grip Index in section '4.6.1 - Calculating Simplified Grip Index'.

4.6.4 2DOF Step Grip Study

The 2DOF system will only take into consideration sprung and unsprung mass. Therefore, within this section only the ‘Grip Index’ will be analysed. A step profile of 0.1m will be used and in order to increase the vehicle speed, the time in which it takes to reach the top of the step will be decreased from 0.2s to 0.04s in increments of 0.01s, and the ‘Grip Index’ will be noted for each increment. The study will be completed through three methods, first the standard 3,000Ns/m will be evaluated, then the use of Microsoft Excels data solver will be used to determine optimum grip at step duration 0.2, then the third method uses the data solver set to determine optimum grip at each individual step duration.

Table 4-1 - 2DOF Step Grip Results

% Increase	0.1m Step Height	2DOF Damping 3000		Initial Optimised Damping 6109		Optimised Damping	Speed Optimised Damping
	Step Duration	Damping Value (ns/mm)	Grip Index Value	Damping Value (Ns/mm)	Grip Index Value	Damping Value (Ns/mm)	Grip Index Value
0	0.2	3	13.71851556	6.109	16.63149385	6.109	16.63149385
6.25	0.19	3	12.72839081	6.109	15.19655535	5.750	15.21302744
12.5	0.18	3	11.82642021	6.109	13.82737913	5.392	13.90749034
18.75	0.17	3	11.0060901	6.109	12.55153206	5.114	12.73118756
25	0.16	3	10.26135416	6.109	11.38275146	4.882	11.68367505
31.25	0.15	3	9.585991447	6.109	10.32784125	4.698	10.75267171
37.5	0.14	3	8.973953222	6.109	9.384508902	4.533	9.928055027
43.75	0.13	3	8.41981152	6.109	8.547948536	4.382	9.19567196
50	0.12	3	7.918674583	6.109	7.808804129	4.251	8.546847631
56.25	0.11	3	7.465972223	6.109	7.158860628	4.140	7.971184445
62.5	0.1	3	7.059490681	6.109	6.589247952	4.012	7.461385387
68.75	0.09	3	6.697685611	6.109	6.092582051	3.922	7.012766725
75	0.08	3	6.379148159	6.109	5.663531608	3.834	6.623281086
81.25	0.07	3	6.106984842	6.109	5.298729798	3.720	6.292253472
87.5	0.06	3	5.88701545	6.109	5.000947623	3.649	6.025122071
93.75	0.05	3	5.71487774	6.109	4.766348299	3.580	5.818734273
100	0.04	3	5.580408289	6.109	4.582876295	3.580	5.580408289

‘Table 4-1 - 2DOF Step Grip Results’ shows the results of the 2DOF grip study stated previously in this section. From looking at the two right hand columns it can be seen that as the vehicle speed increases, less damping is required* in order to maintain the ‘optimum’ level of grip available.

*Study is based on constant damping value, results may vary for different compression and rebound values

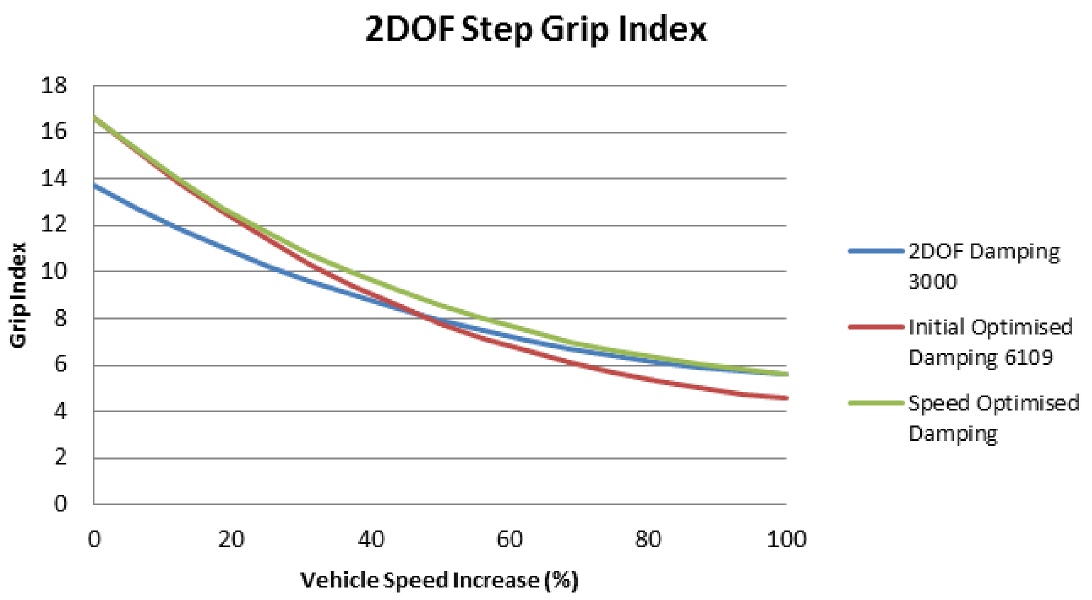

Figure 4-39 - 2DOF Step Grip Index

'Table 4-1' states that as the vehicle speed is increase the damping is decreased to improve the grip performance. However, as shown in 'Figure 4-39', the base setting of 3,000Ns/m proved to provide a reduced grip over the initial optimised damping value of 6,109Ns/m at lower speeds and vice versa at higher speeds. This confirms a necessity of active damping in order to maintain a consistent level of grip performance within this scenario.

4.6.5 2DOF Random Road Grip Study

Using the results from section '4.6.4 - 2DOF Step Grip Study', a random road profile of 10mm variation has been used to determine if the values are adaptable to the different scenario. The study will use the base line damping value of 3,000Ns/m and compare it against the two other proven values from the previous section (6,109Ns/m and 3,580Ns/m). Using Microsoft Excel's data solver set the optimum value for the random road profile will be obtained.

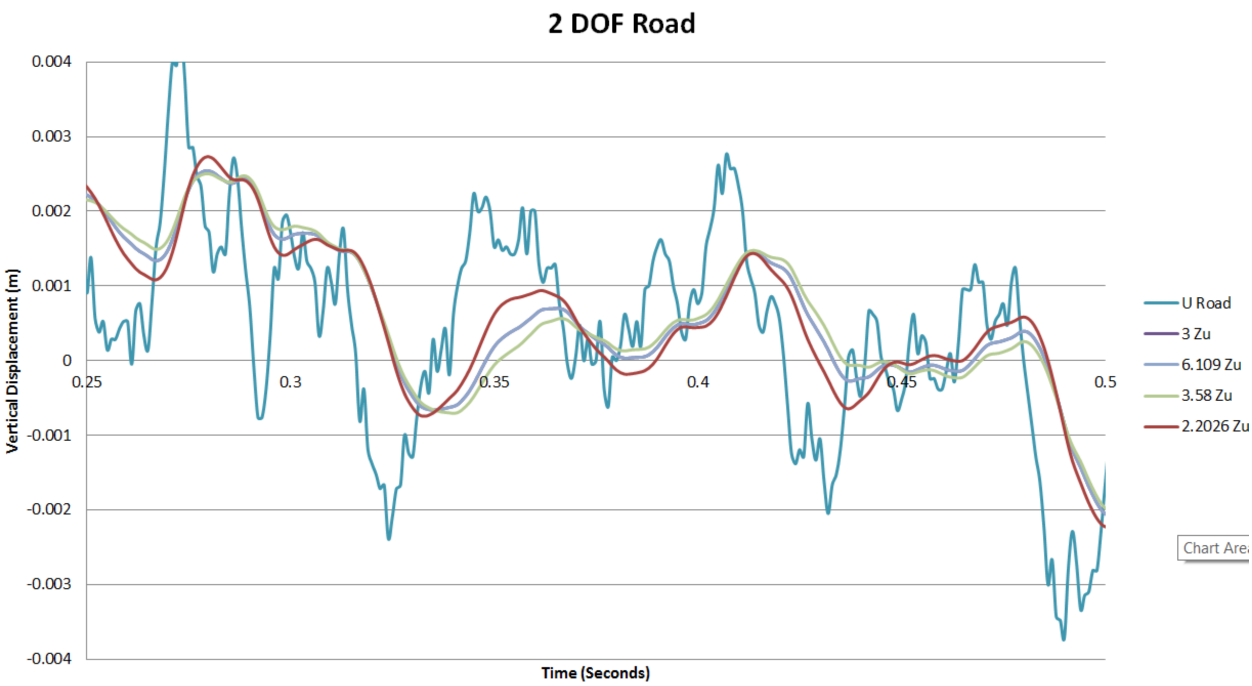

Figure 4-40 - 2DOF Random Road Grip Index

Table 4-2 - 2DOF Random Road Grip Results

Damping Value		Graph Colour	Grip Index
Base line	3	Purple	3.072140406
Step Low Speed Optimum	6.109	Light Purple	2.766044087
Step High Speed Optimum	3.58	Light Green	3.019024099
Road Optimum	2.202602	Red	3.107988265

'Figure 4-40' shows the results of the random road adjustments, whilst 'Table 4-2 - 2DOF Random Road Grip Results' defines the graph. From 'Table 4-2' it can be seen that the 'Road Optimum' damping value of 2,206Ns/m provides the best grip index this can also be seen in 'Figure 4-40' where the 'Road Optimum' trace of Z_u follows the road closest of the four configurations.

The current model has only taken into consideration a 2 degree of freedom model. However, a motorcycle is much more complex and entails more parameters and forces such as rake, compression damping, rebound damping, bump/top out stops, pitch, banking etc… Therefore the model can be developed into a 5 degree of freedom model in order to determine the effects of the other parameters.

4.7 5 Degrees of Freedom

4.7.1 5 Degree of Freedom, Free Body Diagram

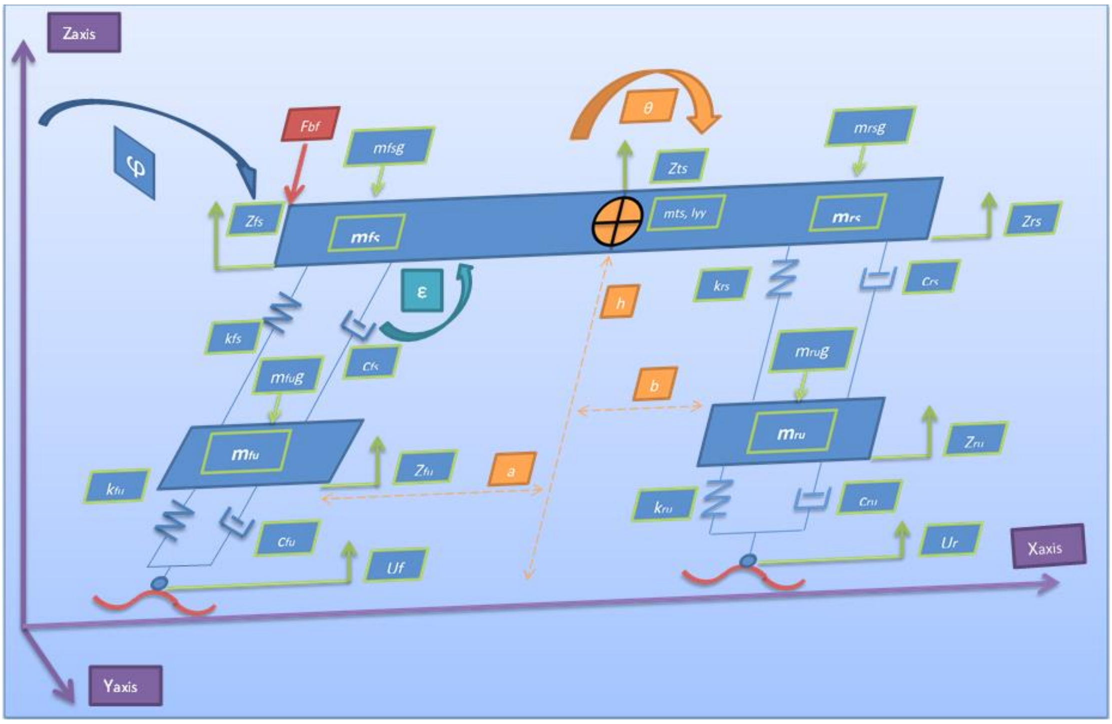

Figure 4-41 - 5 Degree of Freedom Free Body Diagram

'Figure 4-41' shows the free body diagram of a motorcycle which takes into consideration vertical displacement of all 3 masses (the model separates the sprung mass to determine point mass displacements), pitch of the vehicle, roll of the vehicle, braking pressure. Roll and Brake pressure are input values into the system; this is so that real time data obtained through data logging can be implemented into the model so that developments to the vehicle's suspension can be made away from the vehicle and prior to testing. The purpose of this is to improve vehicle handling and safety prior to operating the vehicle.

4.7.2 5 Degree of Freedom Model Formulation

Equation 4-46

$$\boldsymbol{m_{fu}} * \boldsymbol{\ddot{Z}_{fu}}[N] = \left(\begin{array}{c} \{K_{fu} * (U_f - Z_{fu}) * \cos\varphi\} + \{C_{fu} * (\dot{U_f} - \dot{Z_{fu}})\} + \\ + \left\{K_{fseff} * \left((Z_{fs} + \theta * a) - Z_{fu}\right) * \cos\varphi\right\} + \left\{C_{fs} * \left((\dot{Z_{fs}} + \dot{\theta} * a) - \dot{Z_{fu}}\right)\right\} - \{m_{fu} * g\} \end{array} \right) * \mu_{ground}$$

Equation 4-47

$$\boldsymbol{m_{ru}} * \boldsymbol{\ddot{Z}_{ru}}[\boldsymbol{N}] = (\{K_{ru} * (U_r - Z_{ru}) * \cos\varphi\} + \{C_{ru} * (\dot{U}_r - \dot{Z}_{ru})\}$$
$$+ \left\{K_{rs} * \left((Z_{rs} - \theta * b) - Z_{ru}\right) * \cos\varphi\right\} + \left\{C_{rs} * \left((\dot{Z}_{rs} - \dot{\theta} * b) - \dot{Z}_{ru}\right)\right\}$$
$$- \{m_{ru} * g\}\Big) * \mu_{ground}$$

Equation 4-48

$$\boldsymbol{m_{fs}} * \boldsymbol{\ddot{Z}_{fs}}[\boldsymbol{N}] = \left(\left\{K_{fseff} * \left(Z_{fu} - (Z_{fs} + \theta * a)\right) * \cos\varphi\right\} + \left\{C_{fs} * \left(\dot{Z}_{fu} - (\dot{Z}_{fs} + \dot{\theta} * a)\right)\right\}\right.$$
$$\left. - \left\{\frac{F_{bf} * h}{a + b}\right\} - \{m_{fs} * g\}\right)$$

Equation 4-49

$$\boldsymbol{m_{rs}} * \boldsymbol{\ddot{Z}_{rs}}[\boldsymbol{N}] = \left(\{K_{rs} * (Z_{ru} - (Z_{rs} + \theta * b)) * \cos\varphi\} + \left\{C_{rs} * \left(\dot{Z}_{ru} - (\dot{Z}_{rs} + \dot{\theta} * b)\right)\right\}\right.$$
$$\left. + \left\{\frac{F_{bf} * h}{a + b}\right\} - \{m_{rs} * g\}\right)$$

Equation 4-50

$$\boldsymbol{I_{yy}} * \boldsymbol{\ddot{\theta}}[\boldsymbol{Nm}] = \left[\left(\left\{K_{fseff} * \left(Z_{fu} - (Z_{fs} + \theta * a)\right) * \cos(\varphi) * a\right\}\right.\right.$$
$$\left.\left. + \left\{C_{fs} * \left(\dot{Z}_{fu} - (\dot{Z}_{fs} + \dot{\theta} * a)\right) * a\right\} - \left\{\frac{F_{bf} * h}{a + b}\right\} * a - \{m_{fs} * g * a\}\right)\right]$$
$$- \left[\left(\{K_{rs} * (Z_{ru} - (Z_{rs} + \theta * b)) * \cos(\varphi) * b\}\right.\right.$$
$$\left.\left. + \left\{C_{rs} * \left(\dot{Z}_{ru} - (\dot{Z}_{rs} + \dot{\theta} * b)\right) * b\right\} + \left\{\frac{F_{bf} * h}{a + b}\right\} * b - \{m_{rs} * g * b\}\right)\right]$$

Equation 4-51

$$\boldsymbol{m_s} * \boldsymbol{\ddot{Z}_t}[\boldsymbol{N}] = \left[\left(\left\{K_{fseff} * \left(Z_{fu} - (Z_{fs} + \theta * a)\right) * \cos\varphi\right\}\right.\right.$$
$$\left. + \left\{C_{fs} * \left(\dot{Z}_{fu} - (\dot{Z}_{fs} + \dot{\theta} * a)\right)\right\} - \left\{\frac{F_{bf} * h}{a + b}\right\} - \{m_{fs} * g\}\right)$$
$$+ \left(\{K_{rs} * (Z_{ru} - (Z_{rs} + \theta * b)) * \cos\varphi\} + \left\{C_{rs} * \left(\dot{Z}_{ru} - (\dot{Z}_{rs} + \dot{\theta} * b)\right)\right\}\right.$$
$$\left.\left. + \left\{\frac{F_{bf} * h}{a + b}\right\} - \{m_{rs} * g\}\right)\right]$$

Equation 4-52

$$F_{bf}[N] = \frac{\left[(P_{brakeline}*100{,}000)*\left(2\pi\left(\left(\frac{{d_{p1}}^2}{4}\right)+\left(\frac{{d_{p2}}^2}{4}\right)\right)\right)*\mu_{pad}*\left(\frac{d_{disc}-h_{pad}}{2-g_{pad}}\right)\right]}{\left[\frac{t_{fw}*\frac{t_{fa}}{100}*2+t_{fd}*24.5}{2000}\right]} \quad \text{(Catto, 2013)}$$

The given F_{bf} provides the brake force which is used within the sprung mass equations, the equation provides a conversion between brake line pressure (measured in bar), to the brake force acting on the system (measured in N). Initially the brake force was applied at the wheel as this is where the braking would be applied in application. However, through extensive testing and manipulation, the results consistently provided unrealistic solutions. Therefore, the braking equation within the sprung formulation was created, which provides realistic suspension movement in relation to braking and was confirmed by the data obtained through ‘Be Wiser Kawasaki Superstock Race Team’. The given parameters found in section ‘4.1 Vehicle Parameters’ are the parameters of the ‘Be Wiser Kawasaki’ ZX10R which was used at Knock Hill Race Circuit, Scotland, British Superbike Event Round 5, 14/06/2013. The datalogging showed that when the rider reached 12 Bar of brake line pressure, then the front suspension travel was 110mm, from ‘Figure 4-42’ it can be seen that the rider reaches 12 Bar of brake pressure and the front suspension travel is 105mm.

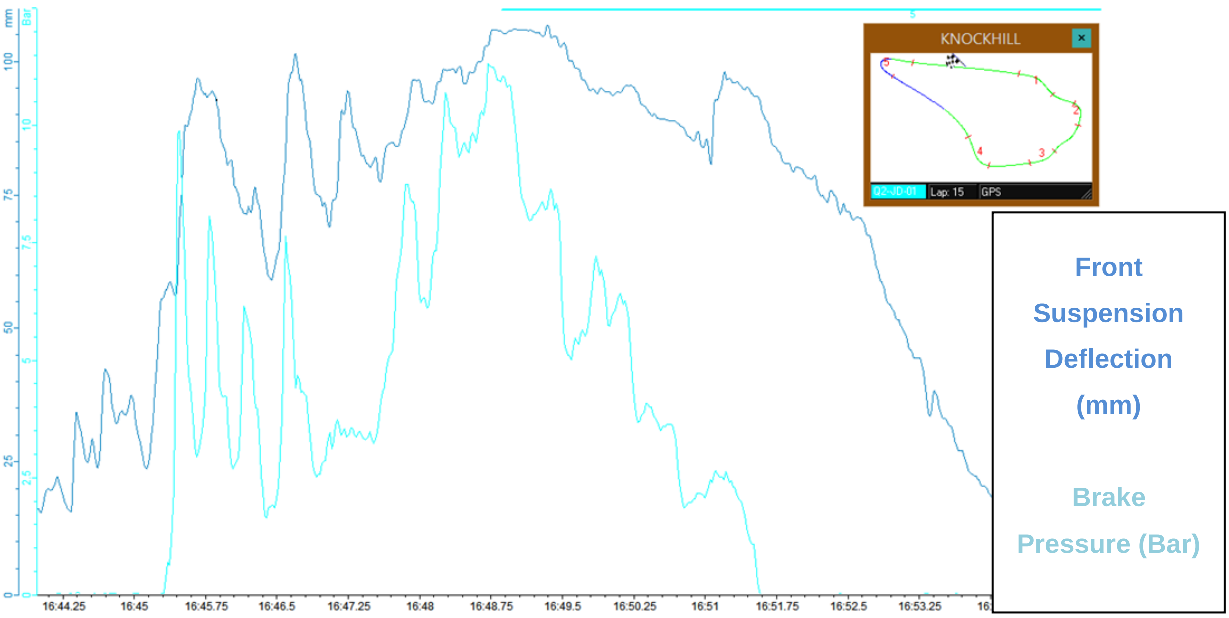

Figure 4-42 - Be Wiser Kawasaki ZX10R Knock Hill Data

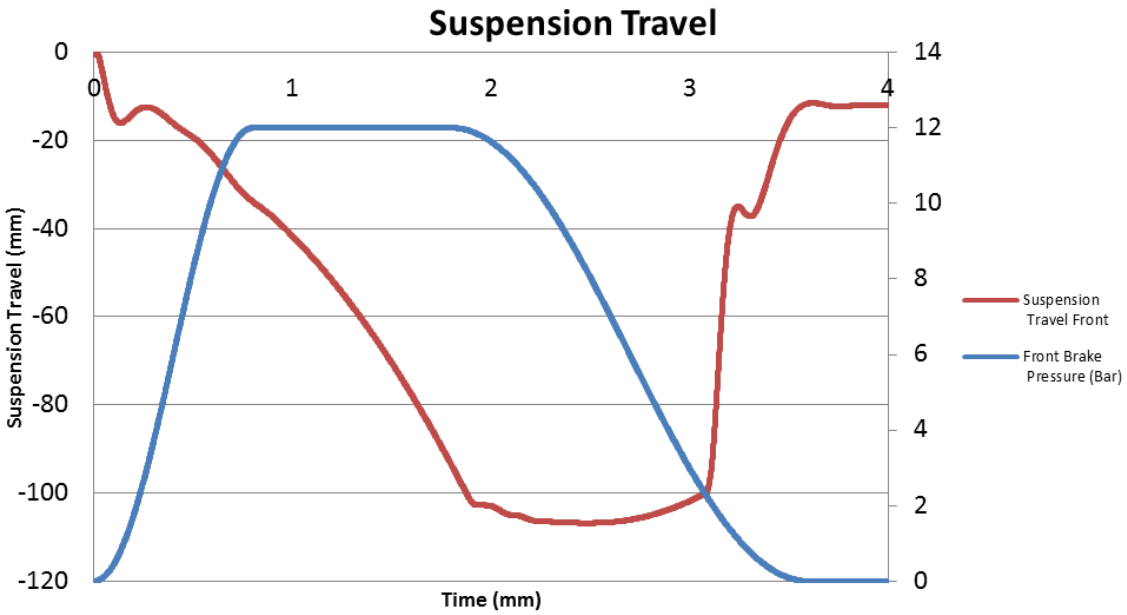

Figure 4-43 - 5DOF Braking Validation

'Figure 4-43' shows the front suspension travel and the braking pressure in the lines so that it can be compared to that of the real data obtained from 'Be Wiser Kawasaki'. It can be seen that the 5DOF model uses a smoothed braking force which was created through the use of two step profiles which gives the effect of a large ramped braking force. However, the real data shows the braking to be rather irregular, the 5DOF model shows the suspension hits the bump stops just as the brake is being released and it is not until 2Bar of brake pressure that the suspension releases from the bump stop. When comparing this to 'Be Wiser Kawasaki's' data we can assume that if the rider's braking was smoother and similar to that of the created braking in the model, then the logged data would show the same if not similar results, it is also possible to state that, the erratic braking method is preventing grip and stability within the vehicle and that the rider could benefit, in the terms of lap times, from smoothing his braking process, as this would create a lower variation of force acting through the front tyre and increase grip. However, if the rider was to do so, then it is clear that higher spring stiffness would be needed to ensure that the rider does not reach the bump stops.

4.8 5 Degree of Freedom Grip Study

This grip study will be performed in the identical manor of that of the 2DOF grip study. Primarily the simulation will be run over a step profile and through using Microsoft Excel's Data Solver tool; the optimised damping values will be obtained. The study will compare the base line damping grip results against that of the optimised, and will compare the Grip Index, Heave Index and Pitch Index against each other stating the compromise between the results. The study will go on to analyses the effects which braking and banking have on the indexes and will run the solver against each scenario to obtain adequate data for a conclusion. The results of the 2DOF grip study will be compared to that of the 5DOF grip study in order to determine if the constant damping value's (rebound and compression equal to each other) used, provided a similar results with the 5DOF model.

4.8.1 5 Degree of Freedom Constant Damping Grip Study

This section of the study compares the results of the 2DOF grip study with the base damping value of 3,000Ns/m with the 5DOF system with the same damping values. 'Figure 4-44' clearly shows that the influence of rear sprung mass and rear unsprung mass severely affect the grip index, and that the in order to accurately determine a method to optimise grip, then a full 5DOF vehicle model should be used. Therefore, the remainder of this document will only consist of 5 degree of freedom models. However, it can be stated that the grip depreciates in a similar manor, suggesting that a 2 degree of freedom model can be used as a quick analysis to determine whether the adjustments would improve the given issue. However, the two degree of freedom model would not show any compromises within the adjustments, i.e. if the adjustment affects the front or rear grip, heave comfort or pitch comfort. Therefore, in order to develop a vehicle properly, it would still be suggested that the 5 degree of freedom model would be used, to ensure that additional problems were not created from the initial development.

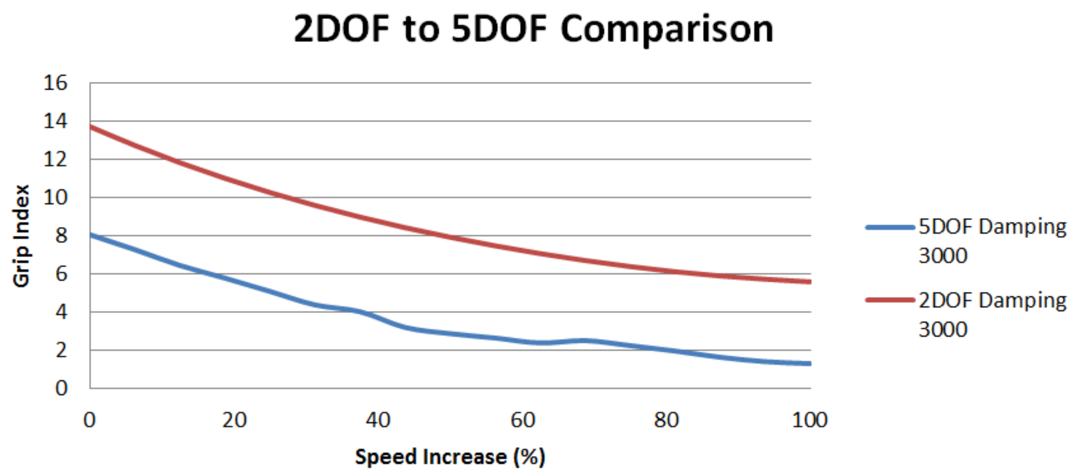

Figure 4-44 - 2DOF to 5DOF Comparison

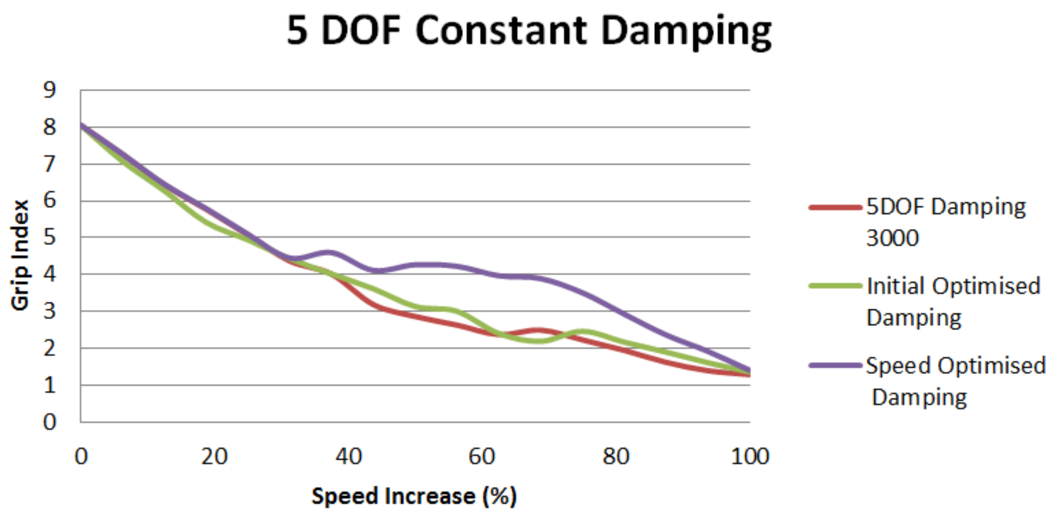

Figure 4-45 - 5 DOF Constant Damping Grip Index

‘Figure 4-45’ shows the results of the ‘Front Grip Index’ for the proposed study within this section of the report. It can be seen that the grip can be increased when traveling between 40 to 85% faster than the base speed over the step profile.

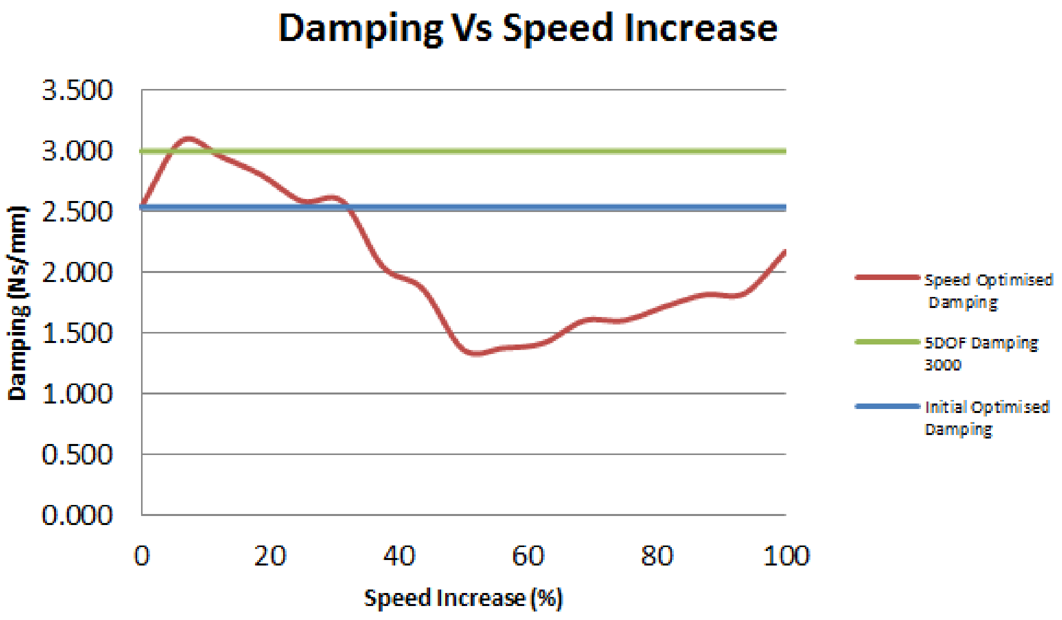

Figure 4-46 - 5DOF Damping vs. Speed

'Figure 4-46' shows that in order to maintain a maximum grip index the damping has to vary by 1.5Ns/mm. Thus, stating a need for at least variable constant damping if not variable compression and rebound damping.

Table 4-3 - 5 DOF Constant Damping Results

5DOF Damping 3000				
Damping (ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort	Pitch Index
3.000	8.050	6.759	4.136	4.996
3.000	7.266	5.651	4.188	4.996
3.000	6.440	4.642	4.266	4.997
3.000	5.775	3.914	4.317	4.997
3.000	5.080	3.199	4.413	4.998
3.000	4.371	2.636	4.509	4.999
3.000	4.014	2.291	4.538	4.999
3.000	3.190	1.652	4.614	4.999
3.000	2.866	1.511	4.625	4.999
3.000	2.635	1.393	4.643	4.999
3.000	2.376	1.303	4.655	4.999
3.000	2.497	3.401	4.460	4.997
3.000	2.234	3.475	4.465	4.997
3.000	1.950	2.855	4.516	4.997
3.000	1.626	1.942	4.628	4.998
3.000	1.397	1.503	4.679	4.998
3.000	1.291	1.147	4.625	4.998

Initial Optimised Damping				
Damping (ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort	Pitch Index
2.541	8.056	6.677	4.163	4.996
2.541	7.078	5.533	4.217	4.997
2.541	6.277	4.553	4.305	4.997
2.541	5.419	3.081	4.426	4.998
2.541	4.944	2.671	4.455	4.998
2.541	4.434	2.616	4.517	4.999
2.541	4.020	2.301	4.534	4.999
2.541	3.618	2.020	4.567	4.999
2.541	3.139	1.526	4.624	4.999
2.541	3.005	1.635	4.594	4.999
2.541	2.407	1.258	4.673	4.999
2.541	2.192	1.114	4.695	4.999
2.541	2.465	3.561	4.507	4.998
2.541	2.171	2.679	4.562	4.998
2.541	1.902	1.931	4.614	4.998
2.541	1.613	1.506	4.665	4.998
2.541	1.361	1.156	4.623	4.998

Speed Optimised Damping				
Damping (ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort	Pitch Index
2.541	8.056	6.677	4.163	4.996
3.087	7.270	5.667	4.184	4.996
2.952	6.456	4.649	4.267	4.997
2.802	5.793	3.903	4.319	4.998
2.587	5.098	3.184	4.417	4.998
2.587	4.452	2.483	4.524	4.999
2.048	4.599	4.399	4.388	4.998
1.862	4.116	3.701	4.431	4.998
1.363	4.269	2.113	4.510	4.999
1.375	4.227	1.897	4.533	4.999
1.419	3.971	1.655	4.562	4.999
1.603	3.895	1.823	4.445	4.998
1.604	3.510	3.483	4.495	4.998
1.718	2.932	2.741	4.529	4.998
1.817	2.366	1.914	4.609	4.998
1.830	1.923	1.502	4.662	4.998
2.173	1.408	1.156	4.636	4.999

From ‘Table 4-3’ it can be seen that as the speed of the vehicle increases, then the heave and pitch comfort increases, which could be identified as the a result of the high spring stiffness as, the stiffer spring could provide better support at higher speeds allowing the suspension to settle quicker, maintaining a consistent comfort values, as the softer spring would create more oscillations creating a lower level of comfort. However, the comfort value is worse at the lower speeds, this is could be due to the longer duration between the front and rear traveling over the step at the lower speeds, which can create a ‘see saw’ effect, thus, causing discomfort.

The trend of the results so far prove that the faster the speed is whilst traveling over a step profile, the less damping is required in order to maintain grip. However, the only study's which have been performed so far are those which consist of constant damping (equal compression damping to rebound damping). Therefore, it is deemed necessary to study the effects of adjusting compression and rebound damping to improve grip within the 5DOF model.

4.8.2 5 Degree of Freedom Finalised Step Profile Grip Study

Within this section of the report the 5 degree of freedom model, with rebound and compression damping implemented, will be analysed against the results of the 5 degree of freedom with the constant damping values.

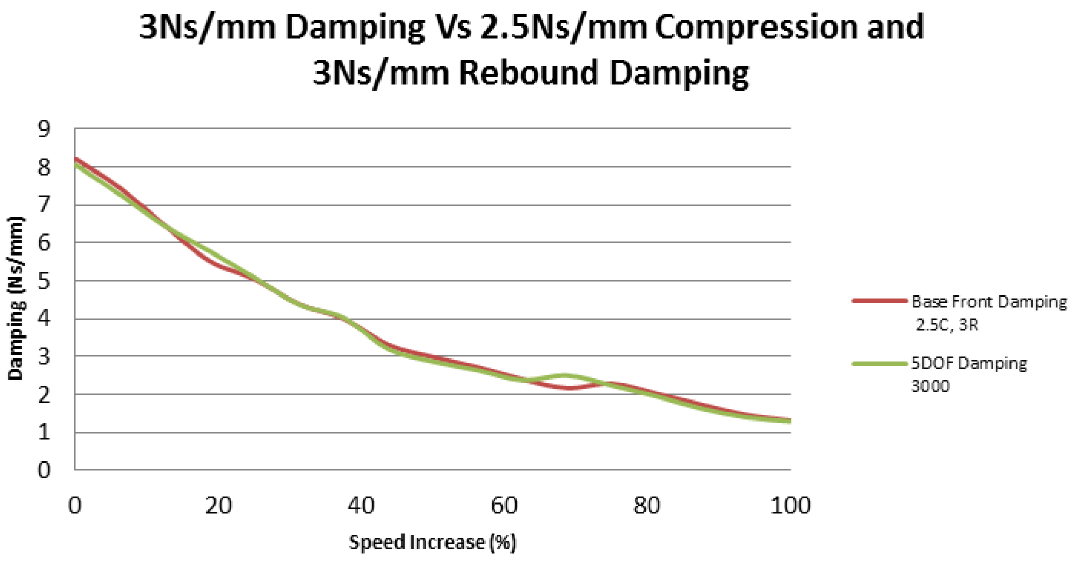

Figure 4-47 - Constant Damping vs. Compression and Rebound Damping, Base Values

'Figure 4-47' shows the effects of having different values for compression and rebound damping. It can be seen that there is a difference in grip from the results and that in areas the grip is marginally better and other marginally worse. However, this graph does state that if there is scope for better suspension, however little, then there is scope for development of grip through different compression and rebound damping values.

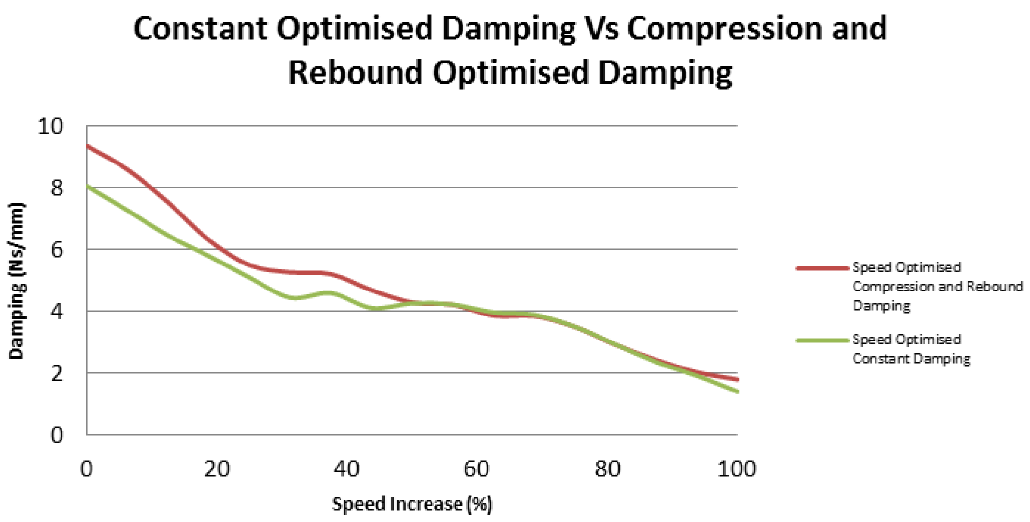

Figure 4-48 - Constant Damping vs. Compression and Rebound Damping

'Figure 4-48' shows, through use of Microsoft Excel's Solver, that using compression and rebound damping can improve grip over the whole range. It can be seen that as the speed is increased the damping ratio between compression and rebound tends towards the value of 1 as it is following the same profile as the constant damping curve (Green), this can also be seen in the table 'Table 4-4' below.

Table 4-4 - Speed Optimised Compression and Rebound Results

Speed Optimised Compression and Rebound Damping						
Damping Compression (Ns/mm)	Damping Rebound (Ns/mm)	Front Active	Rear Active	Heave Active	Pitch Active	Compression / Rebound Ratio
8.5707	6.055956	9.356627	7.171702	3.867386	4.992591	1.415251305
7.520451	4.121369	8.594544	6.031246	3.968093	4.994438	1.824745838
7.520451	4.121369	7.523862	5.010533	4.070019	4.996067	1.824745838
7.844621	4.376123	6.308629	4.161386	4.19073	4.997367	1.792596029
1.591278	1.687716	5.499309	3.679109	4.347953	4.997499	0.942858855
1.584613	1.977942	5.269587	3.947304	4.356666	4.997643	0.801142036
6.11476	1.707695	5.211076	4.535345	4.136825	4.991553	3.580708719
7.627511	4.416086	4.688529	5.561089	4.179366	4.99233	1.727210818
0.887914	2.704916	4.296378	4.057481	4.458781	4.998348	0.328259271
1.3	1.7	4.220662	1.882997	4.534452	4.99866	0.764705882
1.3	1.75	3.870053	1.697732	4.56405	4.998788	0.742857143
1.6	1.7	3.85595	1.816322	4.479509	4.998075	0.941176471
1.6	1.7	3.507744	3.410987	4.496376	4.998143	0.941176471
1.7	1.7	2.924266	2.740857	4.529064	4.998046	1
2.999711	1.504562	2.433105	1.90744	4.596799	4.997794	1.993744235
3.000154	1.502362	2.034239	1.568132	4.648158	4.998149	1.996958754
4.53733	1.361968	1.801918	1.272353	4.594111	4.997824	3.331451147

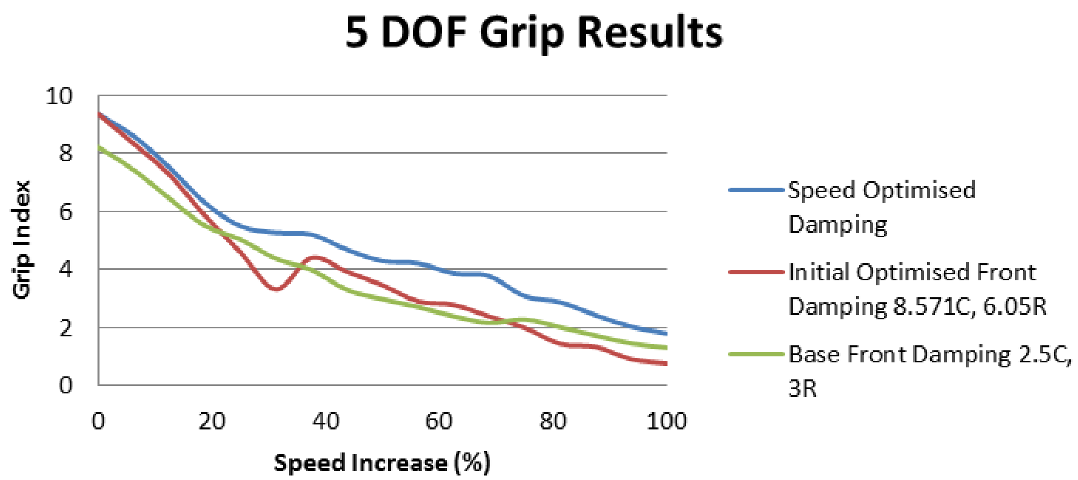

Figure 4-49 - 5DOF Grip Results

'Figure 4-49' shows the results of the 5DOF grip study, it can be seen that if the grip is initially optimised then the rider could suffer dramatically when traveling 30% faster. For example, if the suspension technician were to back off their development due to this issue, the rider would have to increase his speed by 40% on reduced grip and the technician would most likely refrain from adding that development again. Therefore, the suspension technician would unknowingly prevent the rider from achieving maximum grip and possibly develop the motorcycle in the wrong direction and make the vehicle worse.

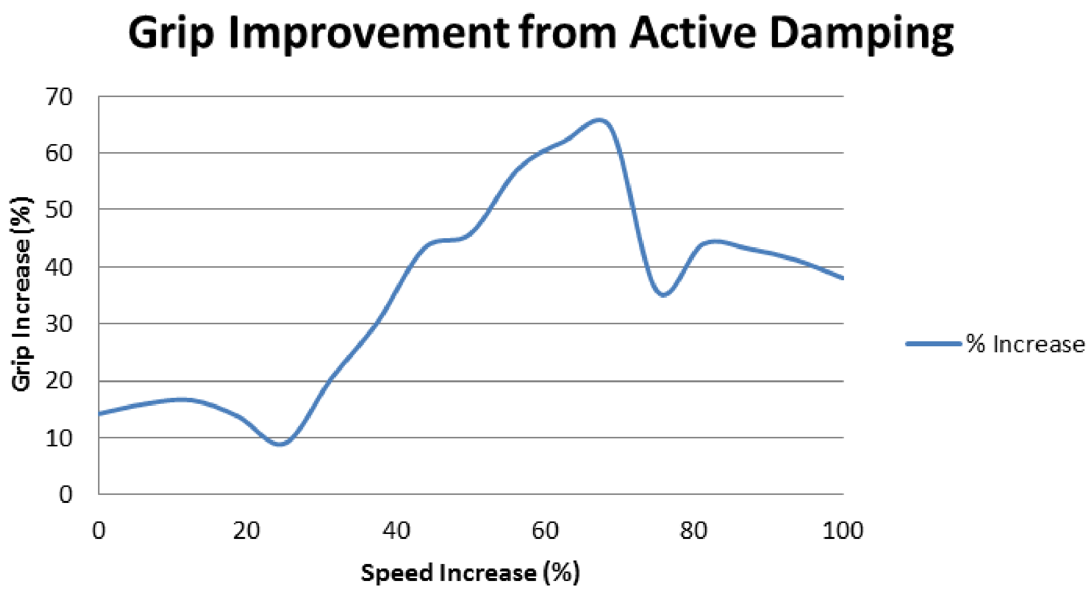

Figure 4-50 - Grip Improvement from Active Damping

'Figure 4-50' shows the grip improvement between active damping (using Microsoft Excel's Solver) and the base damping settings of 2,500Ns/m compression and

3,000Ns/m rebound. The graph states that with an active suspension system there is a front grip increase of up to 65% to be gained.

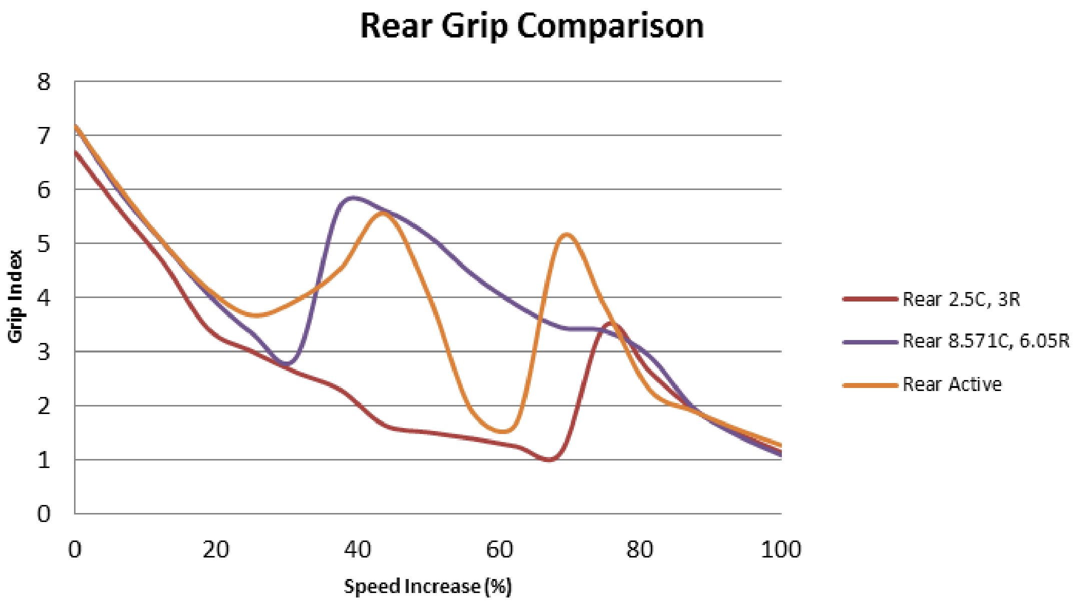

Figure 4-51 - Front to Rear Grip Comparison

'Figure 4-51' shows the effects which front damping have on rear grip. Within this study only the front compression and front rebound damping have been adjusted to optimise the 'Front Grip Index'. It can be seen that the front suspension properties can have a large effect on the rear grip of the vehicle. Therefore, this concludes the statement made in section '4.8.1' "In order to develop a vehicle it would still be suggested that the 5 degree of freedom model was used, to ensure that additional problems are not created from the initial development". From 'Figure 4-51' it can be seen that the developments made to the front suspension have only increased the rear grip when comparing two modified (active and 8.571C, 6.05R) against the base value of 2.5C, 3R. However, 'Figure 4-51' does show that the active front damping reduces rear grip when providing a 45 to 60% vehicle speed increase. Therefore, it would be suggested that a front and rear active damping system was used, to give all round grip, otherwise a grip compromise could be made in order to optimise one area of the vehicle. However, if a full active system was used then the suspension damping could be continuously changing so that the damping could be different at the beginning middle and end of the step profile. However, this model formulation within Microsoft Excel would be rather time consuming and very error prone, due to the nature of the model. Therefore, it can be suggested that this type of active suspension system should be modelled in a multi-body systems software package using complex control algorithms.

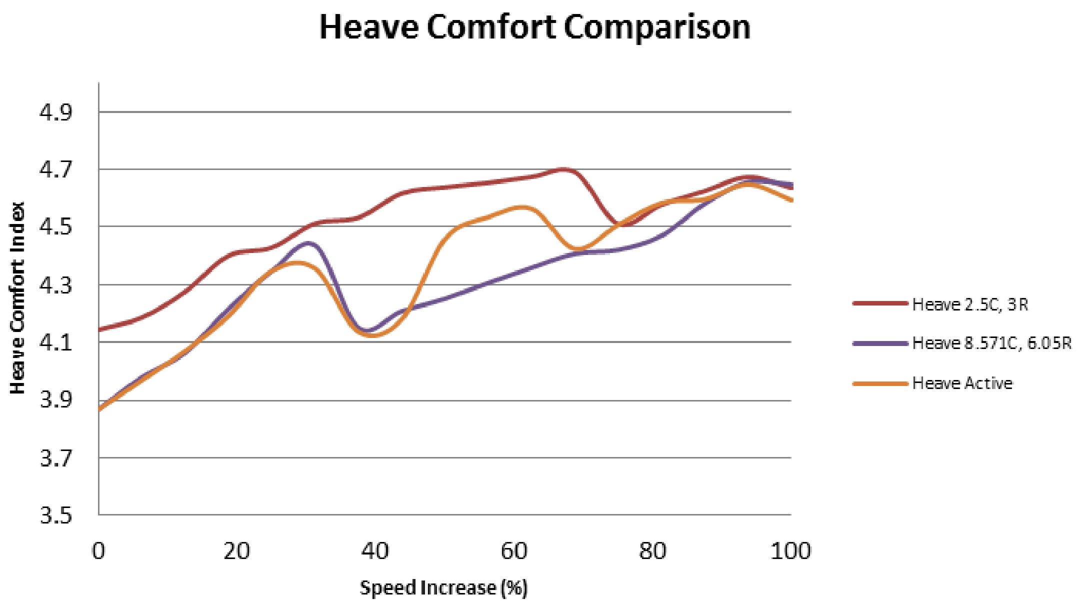

Figure 4-52 - 5DOF Heave Comfort Comparison

'Figure 4-52' shows the effect of front suspension damping against heave comfort, the above figure states that as the grip has been increased, the heave comfort has decreased, this states that the acceleration forces are larger through the system within the optimised damping and active damping settings. This is expected as the damping is trying to reduce the forces through the tyre by sending them through the vehicle and damping them within the suspension. It can be stated that as the threshold has been set as 5m/s^2 in accordance to ISO2631 (International Standard, 2009), that if the Heave or Pitch comfort index reaches 0m/s^2 then the vehicle would be 'unridable'. The term 'unridable' has been quoted as; the vehicle would still operate and possibly give good grip. However, the discomfort of riding the vehicle would psychologically upset the rider, making them feel unsafe and deem the vehicle 'unridable'.

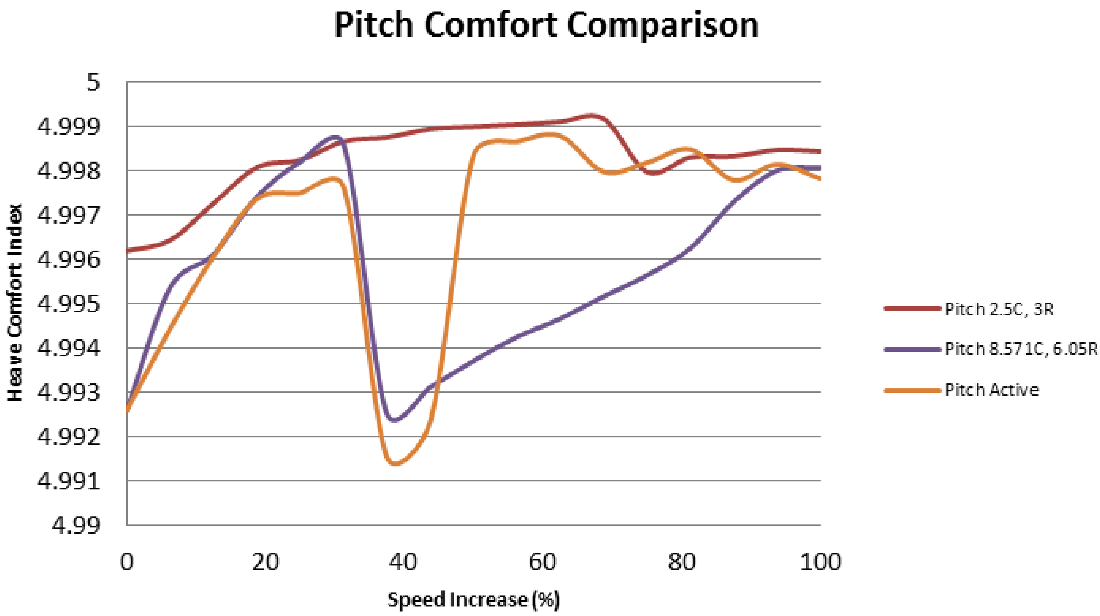

Figure 4-53 - 5DOF Pitch Comfort Comparison

'Figure 4-53' shows the effect of front suspension damping against pitch comfort, the above figure states that as the grip has been increased the pitch comfort has diminished slightly as a result. It can be seen from the graph, that the front suspension damping adjustments only cause a minimal effect to the pitch comfort. Therefore, it can be assumed that the pitch comfort would be more affected by other parameters such as wheelbase, spring stiffness's, vehicle weight, COG position and rake angle.

Using Microsoft Excels Data Table Tool, it has been possible to create the following table which compares different compression and rebound ratios against the step profile duration. The compression and rebound ratio scale is set from 0.1 to 6 and the step duration ranges from 0.2s to 0.04s.

Table 4-5 - Compression/Rebound Ratio vs. Step Duration

Grip Index		Step Duration																
	8.122268	0.2	0.19	0.18	0.17	0.16	0.15	0.14	0.13	0.12	0.11	0.1	0.09	0.08	0.07	0.06	0.05	0.04
Compression to Rebound Damping Ratio	0.1	2.96	2.97	2.20	1.81	1.55	1.28	1.80	1.53	1.27	1.10	0.99	0.65	0.97	0.71	0.60	0.29	0.22
	0.2	5.82	5.27	4.37	3.44	3.01	2.44	3.65	3.23	2.90	2.51	2.04	1.62	1.23	1.14	1.28	0.97	0.83
	0.3	7.08	6.20	5.28	4.76	4.03	3.58	2.84	3.40	2.99	3.09	2.63	2.30	1.90	1.47	1.12	0.93	0.72
	0.4	7.45	6.57	5.86	5.31	4.76	3.91	4.05	3.69	3.41	3.34	3.02	2.65	2.28	1.77	1.34	1.15	1.14
	0.5	7.75	6.82	6.27	5.58	4.97	4.13	4.28	4.01	3.63	3.16	2.36	2.85	2.46	1.85	1.52	1.32	1.23
	0.6	8.07	7.22	6.56	5.84	5.19	4.28	4.40	4.12	3.67	3.01	2.64	2.87	2.56	2.14	1.70	1.47	1.28
	0.7	7.91	7.43	6.69	5.95	5.16	4.89	4.56	4.22	3.48	3.08	2.78	3.09	2.75	2.32	1.91	1.51	1.31
	0.8	7.98	7.42	6.75	5.97	5.34	4.96	4.68	4.19	3.47	3.26	2.89	3.19	2.90	2.53	2.06	1.65	1.32
	0.9	7.79	7.29	6.66	5.31	5.20	5.01	4.68	4.19	3.43	3.33	2.99	3.35	3.06	2.77	2.36	1.91	1.36
	1	7.70	7.07	6.41	5.18	5.23	4.87	4.60	4.11	3.50	3.36	3.03	3.26	3.26	3.05	2.34	1.90	1.37
	1.1	7.56	6.88	6.31	5.56	5.10	4.88	4.45	4.05	3.60	3.39	3.08	3.46	3.67	2.94	2.32	1.90	1.41
	1.2	7.37	6.65	5.52	5.20	4.91	4.72	4.49	3.96	3.47	3.50	2.82	2.70	3.53	2.90	2.28	1.91	1.40
	1.3	7.19	6.47	5.31	5.06	5.06	4.83	4.36	3.82	3.63	3.39	2.82	2.78	3.43	2.86	2.31	1.90	1.42
	1.4	6.97	6.36	5.13	5.10	4.88	4.76	4.35	3.73	3.62	3.36	2.76	3.04	3.42	2.85	2.32	1.92	1.42
	1.5	6.80	6.15	5.01	4.98	4.66	4.74	4.30	3.78	3.59	3.38	2.77	2.89	3.37	2.85	2.32	1.90	1.40
	1.6	6.59	5.99	4.84	4.87	4.54	4.42	4.29	3.63	3.48	3.35	2.77	2.98	3.35	2.82	2.26	1.91	1.41
	1.7	6.45	5.87	4.78	4.77	4.46	4.53	4.13	3.59	3.58	3.35	2.86	2.70	3.33	2.81	2.31	1.90	1.41
	1.8	6.32	5.74	4.84	4.56	4.51	4.45	4.06	3.55	3.53	3.34	2.84	2.69	3.29	2.74	2.33	1.90	1.36
	1.9	6.20	5.63	4.77	4.82	4.45	4.46	4.00	3.54	3.55	3.27	3.20	3.45	3.23	2.73	2.26	1.89	1.37
	2	6.09	5.53	4.75	4.50	4.65	4.42	3.98	3.51	3.53	3.25	2.82	3.43	3.22	2.74	2.32	1.87	1.41
	2.1	5.99	5.40	4.57	4.41	4.34	4.10	3.96	3.47	3.51	3.23	2.80	3.44	3.18	2.71	2.25	1.85	1.40
	2.2	5.90	5.13	4.60	4.33	4.27	4.33	3.90	3.51	3.50	3.24	2.80	3.41	3.22	2.68	2.32	1.87	1.40

	2.3	5.81	5.03	4.53	4.27	4.33	4.25	3.79	3.53	3.48	3.11	2.79	3.34	3.17	2.69	2.25	1.85	1.38
	2.4	5.73	4.94	4.47	4.08	4.28	4.19	3.79	3.44	3.42	3.09	2.79	2.65	3.13	2.66	2.33	1.82	1.37
	2.5	5.62	4.85	4.41	4.00	4.23	4.11	3.74	3.49	3.34	3.15	3.00	3.28	3.15	2.65	2.38	1.81	1.37
	2.6	5.55	4.77	4.37	3.94	4.18	4.04	3.73	3.35	3.42	3.08	3.02	3.30	2.99	2.64	2.34	1.81	1.37
	2.7	5.37	4.60	4.50	3.88	4.13	3.98	3.61	3.36	3.34	3.22	2.98	2.51	2.93	2.62	2.33	1.79	1.40
	2.8	5.33	4.64	4.41	3.82	4.07	4.05	3.58	3.37	3.31	3.08	3.01	3.18	3.11	2.59	2.39	1.80	1.34
	2.9	5.27	4.48	4.33	3.78	4.02	3.99	3.55	3.34	3.29	2.95	2.99	3.17	3.01	2.60	2.35	1.77	1.30
	3	5.22	4.52	4.25	3.72	3.85	3.95	3.51	3.27	3.21	3.00	2.97	2.93	2.98	2.58	2.33	1.75	1.31
	3.1	5.14	4.46	4.20	3.67	4.03	3.92	3.49	3.24	3.19	3.16	3.02	2.90	2.94	2.56	2.40	1.75	1.37
	3.2	5.07	4.32	4.14	3.63	3.99	3.65	3.24	3.23	3.22	3.09	3.02	2.92	3.02	2.54	2.37	1.74	1.40
	3.3	5.04	4.38	4.09	3.59	3.96	3.56	3.18	3.20	3.18	3.09	3.01	2.91	3.01	2.54	2.35	1.73	1.36
	3.4	4.97	4.23	4.06	3.55	3.93	3.46	3.13	3.17	3.16	3.07	2.95	3.03	2.99	2.52	2.33	1.72	1.33
	3.5	4.92	3.99	4.01	3.64	3.89	3.39	3.12	3.18	3.15	3.05	2.93	3.06	2.92	2.51	2.40	1.73	1.34
	3.6	4.88	4.10	3.97	3.62	3.27	3.67	3.07	3.16	3.14	3.00	2.92	3.03	2.92	2.50	2.39	1.73	1.31
	3.7	4.83	4.06	3.93	3.57	3.24	3.64	3.02	3.11	2.96	2.98	2.94	3.01	2.99	2.49	2.35	1.71	1.39
	3.8	4.81	4.05	3.90	3.55	3.20	3.61	3.25	3.08	2.94	2.95	2.93	3.00	2.95	2.42	2.34	1.71	1.38
	3.9	4.78	4.03	3.86	3.52	3.15	3.58	3.24	3.10	2.96	2.92	2.88	3.00	2.93	2.41	2.32	1.70	1.37
	4	4.74	4.00	3.83	3.48	3.12	3.55	3.21	3.08	2.94	2.93	2.85	2.98	2.90	2.40	2.30	1.70	1.36
	4.1	4.70	3.97	3.80	3.47	3.08	3.40	3.19	3.06	2.92	2.92	2.86	2.97	2.90	2.44	2.39	1.68	1.35
	4.2	4.64	3.94	3.78	3.42	3.68	3.37	3.18	3.04	2.90	2.90	2.87	2.97	2.89	2.43	2.38	1.68	1.33
	4.3	4.60	3.92	3.60	3.40	3.66	3.33	3.17	3.04	2.91	2.96	2.85	2.95	2.84	2.41	2.37	1.67	1.26
	4.4	4.58	3.89	3.59	3.38	3.63	3.29	3.12	3.02	2.89	2.91	2.86	2.93	2.84	2.41	2.33	1.67	1.31
	4.5	4.55	3.86	3.56	3.36	3.61	3.27	3.09	3.00	2.88	2.88	2.85	2.93	2.93	2.39	2.32	1.67	1.37
	4.6	4.52	3.85	3.55	3.32	3.55	3.22	3.09	2.97	2.81	2.94	2.40	2.90	2.92	2.39	2.30	1.65	1.37
	4.7	4.48	3.83	3.53	3.31	3.52	3.17	3.07	2.94	2.81	2.92	2.39	2.89	2.90	2.38	2.29	1.65	1.36
	4.8	4.47	3.82	3.51	3.29	3.44	3.15	3.07	2.93	2.74	2.90	2.79	2.88	2.88	2.35	2.28	1.64	1.36
	4.9	4.45	3.79	3.48	3.27	3.39	3.11	3.08	2.91	2.73	2.88	2.78	2.86	2.86	2.33	2.37	1.64	1.35
	5	4.42	3.78	3.43	3.25	3.35	3.09	3.05	2.95	2.79	2.86	2.79	2.87	2.84	2.33	2.36	1.63	1.32

	5.1	4.40	3.75	3.44	3.23	3.51	3.04	3.03	2.93	2.79	2.85	2.78	2.86	2.83	2.31	2.35	1.63	1.32
	5.2	4.37	3.73	3.44	3.20	3.50	3.03	3.02	2.92	2.78	2.83	2.76	2.86	2.83	2.31	2.31	1.63	1.31
	5.3	4.35	3.71	3.38	3.18	3.48	3.01	3.00	2.90	2.75	2.81	2.76	2.85	2.82	2.30	2.30	1.61	1.30
	5.4	4.33	3.69	3.38	3.16	3.46	2.97	2.98	2.89	2.74	2.80	2.76	2.84	2.80	2.30	2.29	1.61	1.28
	5.5	4.30	3.67	3.35	3.13	3.45	2.95	2.96	2.87	2.75	2.78	2.76	2.84	2.78	2.28	2.28	1.61	1.28
	5.6	4.28	3.65	3.34	3.13	3.44	2.93	2.97	2.86	2.72	2.76	2.75	2.33	2.63	2.31	2.27	1.60	1.27
	5.7	4.26	3.64	3.33	3.10	3.43	3.35	2.97	2.85	2.71	2.80	2.75	2.30	2.83	2.30	2.25	1.60	1.26
	5.8	4.24	3.75	3.30	3.08	3.42	3.34	2.91	2.83	2.70	2.78	2.69	2.29	2.82	2.31	2.24	1.60	1.35
	5.9	4.22	3.62	3.29	3.07	3.40	3.32	2.89	2.82	2.58	2.80	2.69	2.29	2.81	2.30	2.24	1.59	1.34
	6	4.20	3.60	3.24	3.06	3.39	3.31	2.86	2.81	2.61	2.80	2.68	2.67	2.80	2.30	2.33	1.59	1.35

‘Table 4-5’ shows, that a compression to rebound ratio of 1 or below provides ‘good’ front grip when traveling at lower speeds. However, ‘Table 4-5’ shows that as the speed increases, the compression damping can be up to 3.5 times stronger to enable maximum grip. It can also be seen that if the ratio is slightly out, then the grip is reduced. Therefore, it could be stated that without the active suspension it can be nearly impossible to provide the highest level of safety for the rider and highest level of grip to enable optimum lap times. The ratios can vary significantly, as at step duration 0.06s a compression of 3.5 stronger is required. When increasing the speed between 0.1s to 0.05s then optimum grip is found by backing off the compression to be only 1.6 times stronger than the rebound. Which is a drastic change in terms of development; however, this drastic change is needed if the vehicle is being developed. Therefore, to optimise the vehicles grip all parameters should be adjusted at the same time as each other. Thus, the study will now use Microsoft Excel’s Solver to modify the vehicle’s front and rear, compression and rebound damping values to optimise the front and rear grip accordingly, to establish the best all round grip over the step profile.

4.8.3 5 Degree of Freedom Front and Rear Optimisation over a Step

This section of the report will take the average grip index of the front and rear tyre and use Microsoft Excel's Solver to optimise the average front and rear grip by adjusting front and rear compression and rebound damping values.

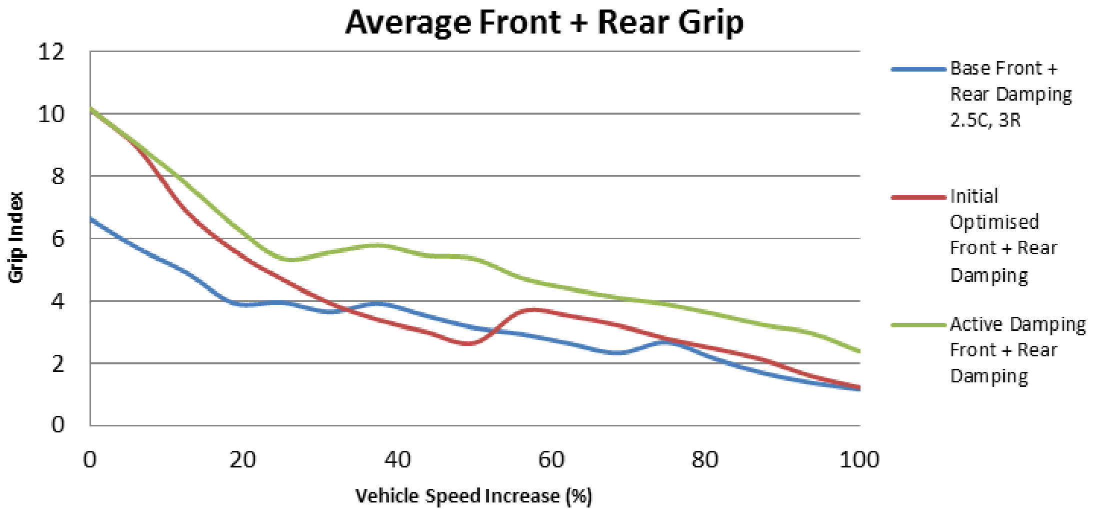

Figure 4-54 - Average Front and Rear Grip Comparisons

'Figure 4-54' shows that with the active front and rear suspension there is the possibility of significant grip gains, for simplicity, the results have been compared against the base values to show a percentage increase in grip, shown below in 'Figure 4-55'. It can be seen from 'Figure 4-55' that there is a significant grip increase to be made when using the active suspension damping, over the base damping values, as the graph states an average grip increase of 66% and a maximum increase of 115% when traveling with a 95% vehicle speed increase.

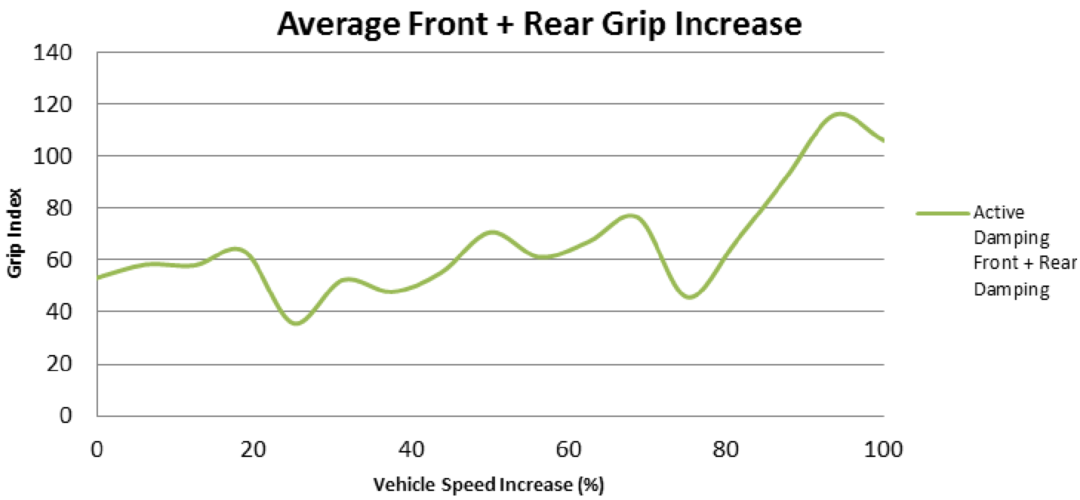

Figure 4-55 - Average Front + Rear Grip Increase

The Microsoft Excel Solver was set to manipulate the front and rear compression and rebound values in order to maximise the average of the front and rear grip index for each speed interval. It could be suggested that perhaps either the front or the rear would have sacrificed some grip in order to maintain an overall high grip index. However, this is not particularly true. From section '4.8.2' it was clear that the adjustment of the front damping values affected the rear grip index. Therefore, using both front and rear active suspension to obtain an overall higher grip, should benefit both the front and rear grip. This can be seen below in 'Figure 4-56 and Figure 4-57'.

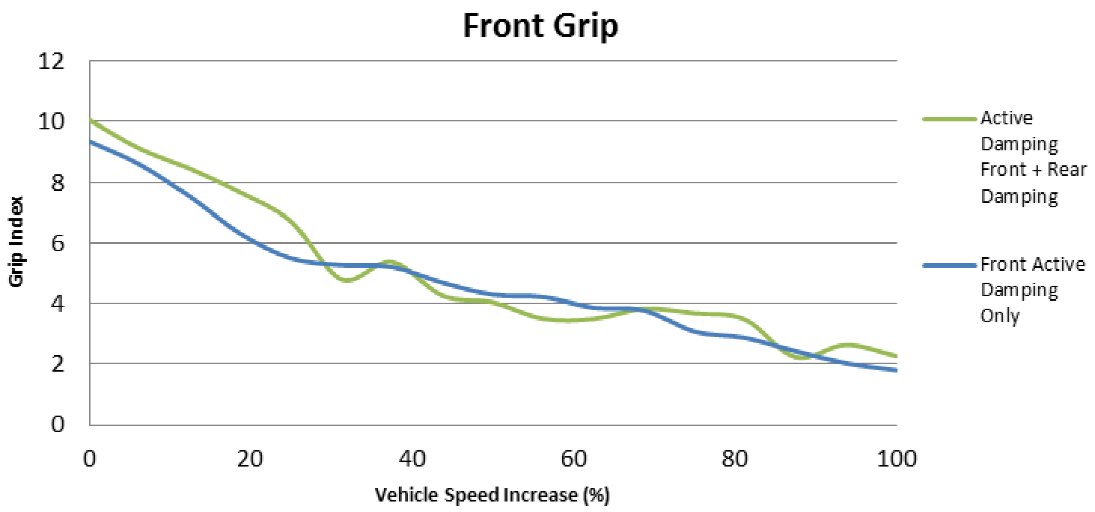

Figure 4-56 - Front Grip Comparison

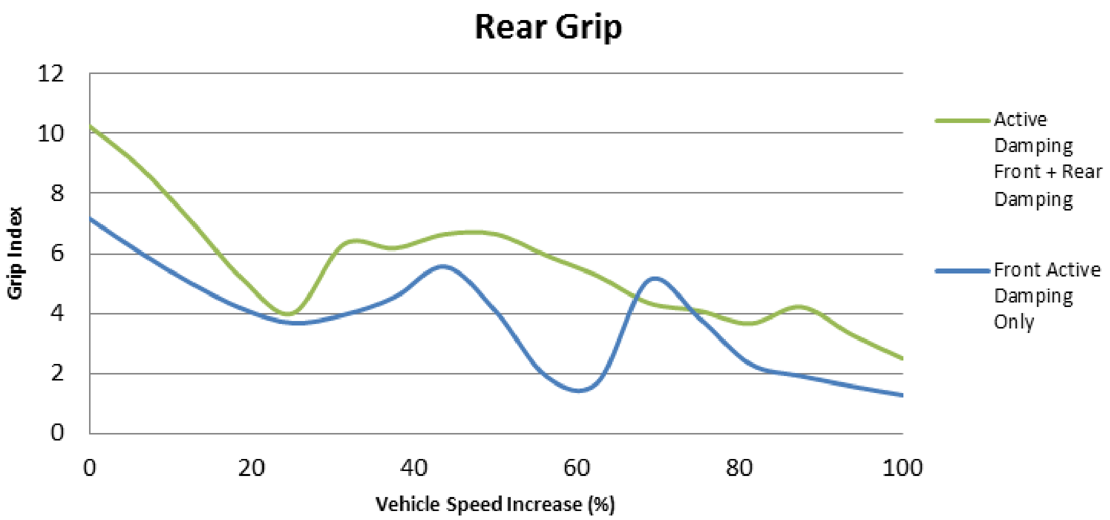

Figure 4-57 - Rear Grip Comparison

As you can see from the two above figures, that the front grip is slightly better in places and slightly worse between 30 to 70% of a vehicle speed increase. However, it can be seen that it is only marginally worse, and that the rear grip gains are better across the board, and only slightly worse at 70%. Therefore, the vehicle would still provide a consistent level of higher grip across the vehicle speed range.

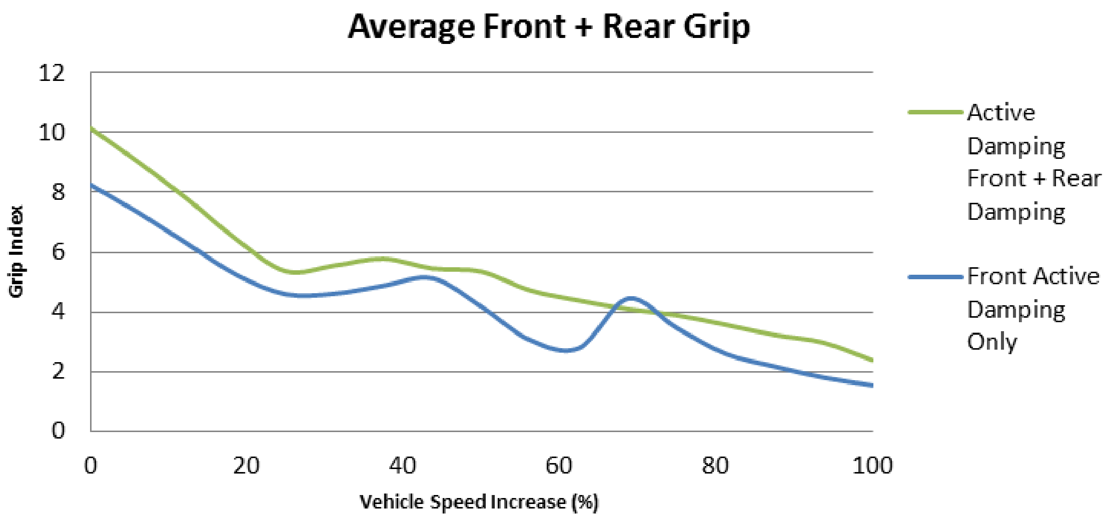

Figure 4-58 - Average Front + Rear Grip Comparison 2

'Figure 4-58' shows the comparison of the 'front and rear grip averages when both front and rear suspension is actively controlled' (Green) against when 'only the front suspension is actively controlled' (Blue). From the graph it can be seen that when both the front and rear damping is actively controlled that the depreciation in grip is much more linear. Therefore, suggesting that the rider would be able to predict the loss of grip and understand its limits, it also shows that there is an increased grip across the vehicle speed increase range, as previously discovered in 'Figure 4-56 and Figure 4-57'.

In section '4.8.2', it was stated that there is an optimum ratio between the damping values for each particular speed increase. From the results within the current section of the report, these ratios have been established and can be seen in 'Figure 4-59'.

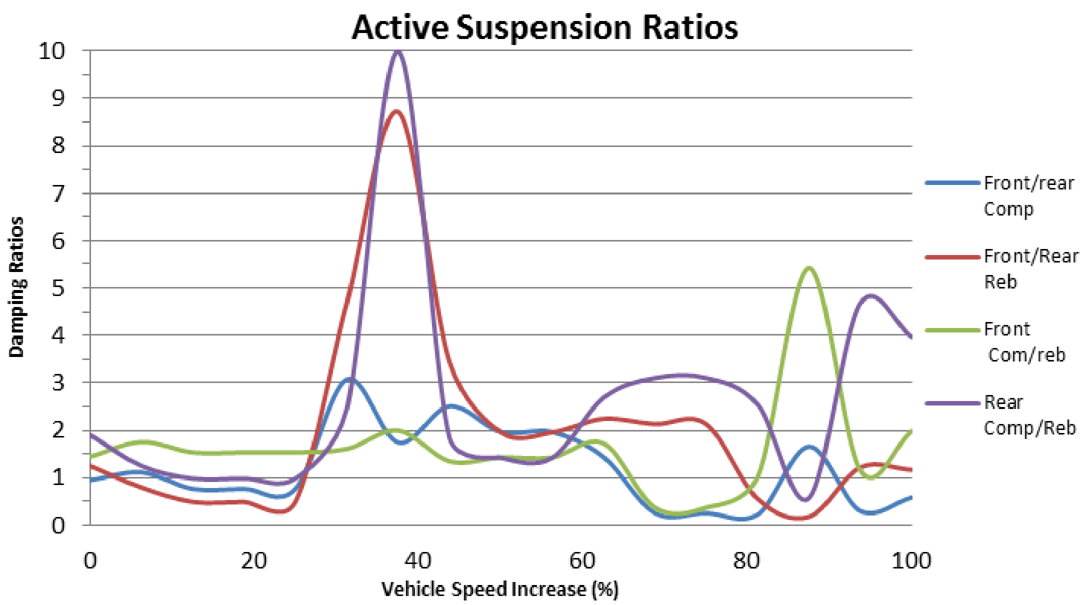

Figure 4-59 - Active Suspension Ratios

‘Figure 4-59’ shows that ratios between the damping values stay fairly similar, as you can see that the ‘Front Compression/Rebound’ and the ‘Rear Compression/Rebound’ follow a close pattern and it can also be seen that ratio between ‘Front to Rear Compression’ and ‘Front to Rear Rebound’ are similar as too. It can be noted that it is not until the vehicle is traveling 75% faster that the trend of the ratio’s change. Therefore, this could be the significance to the basis of an algorithm to optimise active damping suspension based on the GPS Speed of a vehicle.

It can be deemed necessary to study the relationship between front and rear damping ratios. This can be done by optimising the front and rear suspension at the base step duration of 0.2s and then finding the ratio between the damping at the front and rear. Then by manipulating this ratio, with ‘Microsoft Excels Data Table’ tool, we can see which ratios provide the optimal damping. Therefore, creating a more advanced active suspension system, or at least providing more knowledge for an advanced active suspension system.

Table 4-6 - Front to Rear Damping Ratio

Grip Index		Step Duration																
	10.12495	0.2	0.19	0.18	0.17	0.16	0.15	0.14	0.13	0.12	0.11	0.1	0.09	0.08	0.07	0.06	0.05	0.04
Damping Ratio between Front and Rear Values	0.1																	
	0.2																	
	0.3																	
	0.4	8.61	6.68	4.56	4.05	3.56	3.21	2.75	2.29	1.92	1.68	1.44	1.38	0.98	0.87	0.71	0.76	
	0.5	9.07	8.16	5.34	4.59	3.98	3.48	3.07	2.57	2.22	1.94	1.70	1.55	1.19	1.04	0.94	1.02	0.83
	0.6	9.39	8.52	6.18	5.22	4.37	3.91	3.31	2.76	2.40	2.09	1.79	1.63	1.29	1.17	1.60	1.18	0.96
	0.7	9.63	8.77	6.66	5.59	4.70	3.97	3.41	2.84	2.48	2.16	1.89	1.67	1.35	1.93	1.81	1.32	1.07
	0.8	9.80	8.84	7.57	5.57	4.63	4.29	3.52	3.00	2.59	2.24	1.96	1.76	1.63	2.49	1.96	1.34	1.12
	0.9	10.03	8.96	7.55	5.77	4.89	4.13	3.63	3.08	2.70	2.34	2.01	1.89	2.64	2.54	2.05	1.44	1.16
	1	10.15	8.98	7.10	5.95	5.00	4.15	3.56	3.12	2.75	2.41	2.08	2.26	2.81	2.57	2.08	1.48	1.18
	1.1	10.12	8.65	7.18	6.03	5.02	4.24	3.58	3.20	2.79	2.47	3.66	3.28	2.77	2.60	2.09	1.53	1.20
	1.2	10.09	8.49	7.10	5.82	5.11	4.24	3.61	3.21	2.81	4.03	3.75	3.32	2.81	2.63	2.11	1.62	1.23
	1.3	9.94	8.41	6.96	5.86	5.13	4.30	3.64	3.31	4.63	4.19	3.83	3.33	2.83	2.64	2.10	1.59	1.24
	1.4	9.76	8.27	6.98	5.86	5.12	4.33	3.71	4.64	4.64	4.31	3.85	3.34	2.85	2.66	2.11	1.58	1.25
	1.5	9.62	8.12	6.87	5.84	4.92	4.25	4.33	5.11	4.63	4.34	3.87	3.37	2.88	2.67	2.12	1.55	1.25
	1.6	9.41	8.02	6.85	5.90	4.90	4.38	4.66	5.36	4.65	4.35	3.88	3.39	2.88	2.67	2.10	1.53	1.26
	1.7	9.25	7.95	6.81	5.83	4.79	4.03	4.87	5.50	4.77	4.40	3.87	3.38	2.88	2.67	2.09	1.51	1.26
	1.8	9.02	7.81	6.71	5.75	4.80	4.55	5.22	5.51	4.85	4.42	3.86	3.39	2.87	2.67	2.07	1.49	1.26
	1.9	8.85	7.65	6.48	5.45	4.78	4.70	5.42	5.43	4.93	4.41	3.86	3.37	2.85	2.66	2.04	1.47	1.26
	2	8.81	7.42	6.14	4.94	5.04	4.84	5.60	5.40	4.92	4.43	3.85	3.35	2.85	2.65	2.02	1.44	1.25
	2.1	8.62	6.85	5.62	5.39	4.52	4.99	5.80	5.35	4.88	4.40	3.83	3.32	2.83	2.64	1.99	1.42	1.25
	2.2	8.05	6.52	6.33	5.09	4.75	5.08	5.85	5.29	4.88	4.36	3.81	3.32	2.82	2.62	1.97	1.40	1.24
	2.3	8.21	6.80	5.53	4.68	4.79	5.23	5.82	5.19	4.83	4.32	3.81	3.30	2.80	2.60	1.95	1.38	1.23
	2.4	7.71	6.44	5.15	4.77	4.80	5.27	5.82	5.13	4.78	4.29	3.77	3.26	2.77	2.58	1.92	1.36	1.22

	2.5	7.39	5.91	5.16	5.83	4.88	5.42	5.76	5.02	4.70	4.22	3.69	3.21	2.73	2.55	1.89	1.35	1.21
	2.6	6.93	6.06	6.21	5.70	4.89	5.47	5.67	4.97	4.61	4.15	3.64	3.16	2.70	2.51	1.86	1.33	1.20
	2.7	7.35	7.12	6.14	5.53	4.88	5.46	5.57	4.95	4.53	4.09	3.58	3.10	2.65	2.47	1.83	1.31	1.19
	2.8	7.92	6.98	5.87	5.53	4.91	5.24	5.47	4.90	4.47	4.03	3.52	3.08	2.62	2.45	1.81	1.29	1.19
	2.9	7.40	6.77	5.53	4.63	4.85	5.38	5.36	4.86	4.42	3.98	3.50	3.04	2.58	2.41	1.79	1.27	1.18
	3	7.28	6.02	4.63	3.99	4.54	5.36	5.27	4.82	4.36	3.93	3.45	2.99	2.55	2.38	1.76	1.25	1.16
	3.1	7.24	5.96	4.54	3.56	4.56	5.29	5.19	4.80	4.31	3.89	3.40	2.95	2.51	2.35	1.74	1.24	1.15
	3.2	6.85	5.53	4.62	3.43	4.41	5.22	5.05	4.70	4.26	3.84	3.35	2.92	2.49	2.32	1.72	1.22	1.13
	3.3	6.46	5.44	4.81	3.39	4.34	5.12	4.89	4.63	4.18	3.77	3.27	2.87	2.43	2.29	1.69	1.21	1.12
	3.4	6.37	5.35	4.93	3.41	4.19	5.01	4.74	4.51	4.06	3.67	3.19	2.80	2.39	2.24	1.66	1.18	1.10
	3.5	6.31	5.07	5.63	3.62	4.03	4.75	4.51	4.38	3.94	3.57	3.11	2.72	2.34	2.19	1.63	1.16	1.08
	3.6	6.22	5.17	6.45	5.16	4.06	4.65	4.34	4.23	3.80	3.43	3.03	2.66	2.28	2.14	1.60	1.14	1.06
	3.7	6.51	5.80	6.46	5.13	4.25	4.85	4.26	4.09	3.73	3.37	2.95	2.60	2.23	2.10	1.57	1.12	1.04
	3.8	6.75	5.21	6.45	5.14	4.78	4.84	4.50	4.14	3.74	3.35	2.93	2.60	2.23	2.09	1.56	1.11	1.04
	3.9	7.64	5.02	6.46	4.98	4.95	5.12	4.63	4.25	3.92	3.56	3.10	2.68	2.28	2.14	1.59	1.12	1.04
	4	7.11	4.01	6.47	4.84	4.82	5.08	4.60	4.32	3.89	3.54	3.09	2.67	2.27	2.13	1.57	1.11	1.03
	4.1	6.33	3.93	6.40	4.66	4.96	5.03	4.56	4.28	3.85	3.51	3.07	2.65	2.26	2.12	1.56	1.10	1.02
	4.2	5.91	4.03	6.39	4.64	4.60	4.96	4.51	4.24	3.81	3.48	3.05	2.62	2.23	2.11	1.55	1.09	1.01
	4.3	5.36	4.16	6.03	4.66	4.60	4.85	4.47	4.19	3.74	3.45	3.03	2.59	2.22	2.09	1.54	1.08	1.01
	4.4	3.84	4.11	6.04	4.08	4.57	4.81	4.40	4.12	3.71	3.40	2.99	2.56	2.19	2.07	1.53	1.06	1.00
	4.5	3.44	2.91	5.74	3.93	4.04	4.63	4.38	4.09	3.61	3.38	2.97	2.54	2.17	2.05	1.51	1.06	0.98
	4.6	3.08	2.88	5.79	3.11	3.88	4.33	4.25	3.96	3.58	3.16	2.91	2.50	2.14	2.01	1.49	1.04	0.96
	4.7	2.92	2.79	5.79	3.06	3.78	4.24	4.23	3.93	3.55	3.13	2.90	2.48	2.12	2.00	1.48	1.04	0.92
	4.8	2.66	2.88	5.83	3.03	3.25	4.38	4.06	3.69	3.32	3.07	2.81	2.35	2.11	1.98	1.47	1.03	0.91
	4.9	2.68	2.39	5.82	3.32	2.93	4.35	3.07	3.58	2.82	2.99	2.80	2.30	2.05	1.94	1.44	1.01	0.89
	5	2.45	2.50	5.80	3.10	2.60	3.24	2.99	3.01	2.73	2.56	2.78	2.04	2.04	1.92	1.43	1.00	0.88
	5.1	2.18	2.08	4.94	2.16	2.42	3.13	2.93	2.91	2.64	2.48	2.25	2.00	2.02	1.91	1.42	0.99	0.84
	5.2	2.33	2.07	4.95	2.33	2.57	2.98	2.76	2.87	2.57	2.42	2.20	1.96	1.70	1.88	1.25	0.91	0.77

	5.3	2.07	2.16	5.01	2.26	2.16	3.13	2.87	2.91	2.62	2.40	2.11	1.97	1.73	1.64	1.22	0.89	0.76
	5.4	2.04	1.91	5.01	2.11	3.02	3.09	2.95	2.83	2.58	2.44	2.20	1.97	1.69	1.61	1.19	0.87	0.74
	5.5	2.22	2.38	4.95	2.11	3.02	3.01	3.42	2.76	2.52	2.39	2.16	2.15	1.83	1.74	1.23	0.89	0.73
	5.6	2.51	3.56	4.93	2.33	3.91	3.77	3.37	3.20	2.86	2.33	2.53	2.13	1.81	1.72	1.34	0.88	0.71
	5.7	2.56	3.63	5.02	3.83	3.86	3.70	3.36	3.16	2.96	2.66	2.49	2.17	1.84	1.74	1.32	0.87	
	5.8	2.53	3.83	4.89	3.82	4.46	3.66	3.47	3.24	2.92	2.76	2.61	2.14	1.82	1.72	1.35	0.91	
	5.9	3.83	3.54	4.85	3.75	3.83	3.85	3.45	3.21	3.04	2.73	2.57	2.21	1.87	1.77	1.33	0.91	
	6	5.44	3.86	4.91	3.72	3.78	3.79	3.61	3.17	3.29	2.84	2.54	2.19	1.84	1.75	1.37	0.91	

From studying ‘Table 4-6’ it is clear to see that when the damping of the vehicle has been optimised for a 0.2s step duration (base speed), that the optimum damping ratio between front to rear stays between the ratios of 1 and 2, i.e. 1 to 2 times stiffer front suspension damping. This was unexpected as, previous vehicle dynamists such as ‘Maurice Olley’ states to provide comfort in ride, it will conform to the ‘flat ride theory’. This is where the rear suspension is stiffer, than the front to cancel out the front movement, or an alternative route is that the rear is controlled so that the overshoots meet and decay to equilibrium at the same time. Thus, providing a more comfortable ride due to minimising any ‘sea saw’ effect (Olley, 1934). ‘Table 4-6’ shows that between a ratio of 1 and 2 of the front and rear damping values, the vehicle has the higher grip indexes. Therefore, the results show the opposite to M. Olley’s flat ride theory of that, when the front is less damped, it allows the front and rear of the vehicle to settle at the same time. However, this does not come of that great surprise, as it is common knowledge that a current vehicle with set suspension cannot be set up for every scenario. Therefore, a compromise always has to be made, the results show that in order to maintain a maximum grip, then the comfort in terms of M. Olley’s flat ride theory has to be sacrificed. However, from looking at the mechanical properties of the vehicle, it can be seen that the front spring stiffness is lower than the rear due to the rake angle. Therefore, in terms of the vehicle’s natural frequencies’, which was what M. Olley focused on, the vehicle still coincides with the ‘flat ride theory’.

‘Table 4-6’ shows that only when traveling at low speeds (between 0.2s and 0.15s) that having a more damped rear benefits the vehicle, this is due to the slow speed of the vehicle, and that the given damping values allow the front to decay to equilibrium prior to the rear of the vehicle reaching the step. Thus, the rear damping can be stronger to increase the grip at the lower speeds. However, it is clear that once the speed has increased (Past 0.15s) that the front is still oscillating whilst the rear of the vehicle hits the step, causing the necessity of stronger front damping.

4.8.4 5 Degree of Freedom Random Road Profile Grip Study

The report has established that in order to maintain a high level of grip, the front and rear suspension both need to be adjusted. Therefore, within this section of the report, the average grip index will still be analysed to develop the damping. The report has focused on the effects of traveling over a step profile and therefore, to develop the knowledge about damping, it has been deemed necessary to evaluate the relationship between random road profiles and damping. Therefore, various random road profiles will be analysed and developed within this section.

Table 4-7 - Random Road Damping Results

Random Road Comparisons											
Damping Description	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index	Front/Rear Comp Ratio	Front/Rear Rebound Ratio
Random Road 1											
Road 1, Base Damping Values	2.5000	3.0000	2.5000	3.0000	2.3341	3.2312	4.6790	4.9898	2.7827	1.00	1.00
Road 1, Initial Step Optimised Damping	8.3218	5.7760	8.8178	4.6247	2.8454	3.5503	4.7754	4.9923	3.1978	1.06	0.80
Road 1, High Speed Step Optimised Damping	3.1300	1.5748	5.3619	1.3512	2.1818	3.2253	4.6830	4.9902	2.7035	1.71	0.86
Road 1, Optimised Damping	**8.3881**	**8.2184**	**6.4984**	**6.2818**	2.8792	3.5971	4.7862	4.9924	3.2381	**0.77**	**0.76**
Road 1, Road 2's Damping	6.4665	6.8240	4.9250	5.3329	2.8469	3.5727	4.7624	4.9918	3.2098	0.76	0.78
Road 1, Road 3's Damping	6.8591	6.7547	5.3166	5.2850	2.8527	3.5813	4.7653	4.9919	3.2170	0.78	0.78
Road 1, Road 4's Damping	6.7057	6.6573	5.2501	5.3388	2.8483	3.5814	4.7639	4.9919	3.2148	0.78	0.80
Road 1, Road 5's Damping	7.0694	7.6379	5.7749	6.0058	2.8667	3.5958	4.7747	4.9921	3.2313	0.82	0.79

Random Road 2											
Road 2, Base Damping Values	2.5000	3.0000	2.5000	3.0000	1.2464	1.6812	4.8536	4.9954	1.4638	1.00	1.00
Road 2, Initial Step Optimised Damping	8.3218	5.7760	8.8178	4.6247	1.4288	1.7168	4.9187	4.9968	1.5728	1.06	0.80
Road 2, High Speed Step Optimised Damping	3.1300	1.5748	5.3619	1.3512	1.1664	1.6474	4.8523	4.9955	1.4069	1.71	0.86
Road 2, Road 1's Damping	8.3881	8.2184	6.4984	6.2818	1.4335	1.7583	4.9238	4.9968	1.5959	0.77	0.76
Road 2 Optimised Damping	**6.4665**	**6.8240**	**4.9250**	**5.3329**	1.4401	1.7840	4.9105	4.9964	1.6120	**0.76**	**0.78**
Road 2, Road 3's Damping	6.8591	6.7547	5.3166	5.2850	1.4403	1.7824	4.9123	4.9965	1.6114	0.78	0.78
Road 2, Road 4's Damping	6.7057	6.6573	5.2501	5.3388	1.4399	1.7834	4.9115	4.9964	1.6116	0.78	0.80
Road 2, Road 5's Damping	7.0694	7.6379	5.7749	6.0058	1.4403	1.7747	4.9176	4.9966	1.6075	0.82	0.79
Random Road 3											
Road 3, Base Damping Values	2.5000	3.0000	2.5000	3.0000	1.2606	1.6963	4.8421	4.9954	1.4784	1.00	1.00
Road 3, Initial Step Optimised Damping	8.3218	5.7760	8.8178	4.6247	1.4455	1.7428	4.9092	4.9969	1.5941	1.06	0.80
Road 3, High Speed Step Optimised Damping	3.1300	1.5748	5.3619	1.3512	1.1937	1.6739	4.8438	4.9955	1.4338	1.71	0.86
Road 3, Road 1's Damping	8.3881	8.2184	6.4984	6.2818	1.4495	1.7775	4.9149	4.9969	1.6135	0.77	0.76
Road 3, Road 2's Damping	6.4665	6.8240	4.9250	5.3329	1.4506	1.7960	4.9016	4.9965	1.6233	0.76	0.78
Road 3, Optimised Damping	6.8591	6.7547	5.3166	5.2850	1.4519	1.7960	4.9034	4.9966	1.6240	**0.78**	**0.78**
Road 3, Road 4's Damping	6.7057	6.6573	5.2501	5.3388	1.4511	1.7966	4.9025	4.9965	1.6239	0.78	0.80
Road 3, Road 5's Damping	7.0694	7.6379	5.7749	6.0058	1.4528	1.7897	4.9085	4.9967	1.6212	0.82	0.79

Random Road 4											
Road 4, Base Damping Values	2.5000	3.0000	2.5000	3.0000	1.2682	1.6914	4.8429	4.9955	1.4798	1.00	1.00
Road 4, Initial Step Optimised Damping	8.3218	5.7760	8.8178	4.6247	1.4328	1.7319	4.9133	4.9970	1.5824	0.80	0.80
Road 4, High Speed Step Optimised Damping	3.1300	1.5748	5.3619	1.3512	1.1997	1.6681	4.8432	4.9958	1.4339	0.86	0.86
Road 4, Road 1's Damping	8.3881	8.2184	6.4984	6.2818	1.4359	1.7653	4.9193	4.9970	1.6006	0.76	0.76
Road 4, Road 2's Damping	6.4665	6.8240	4.9250	5.3329	1.4397	1.7833	4.9057	4.9966	1.6115	0.78	0.78
Road 4, Road 3's Damping	6.8591	6.7547	5.3166	5.2850	1.4405	1.7831	4.9075	4.9967	1.6118	0.78	0.78
Road 4, Optimised Damping	**6.7057**	**6.6573**	**5.2501**	**5.3388**	1.4399	1.7838	4.9066	4.9967	1.6119	**0.80**	**0.80**
Road 4, Road 5's Damping	7.0694	7.6379	5.7749	6.0058	1.4405	1.7775	4.9129	4.9968	1.6090	0.79	0.79
Random Road 5											
Road 5, Base Damping Values	2.5000	3.0000	2.5000	3.0000	1.2231	1.6579	4.8313	4.9958	1.4405	1.00	1.00
Road 5, Initial Step Optimised Damping	8.3218	5.7760	8.8178	4.6247	1.4278	1.7543	4.8978	4.9970	1.5911	1.06	0.80
Road 5, High Speed Step Optimised Damping	3.1300	1.5748	5.3619	1.3512	1.1440	1.6089	4.8290	4.9957	1.3765	1.71	0.86
Road 5, Road 1's Damping	8.3881	8.2184	6.4984	6.2818	1.4409	1.7857	4.9049	4.9970	1.6133	0.77	0.76
Road 5, Road 2's Damping	6.4665	6.8240	4.9250	5.3329	1.4359	1.7889	4.8909	4.9967	1.6124	0.76	0.78
Road 5, Road 3's Damping	6.8591	6.7547	5.3166	5.2850	1.4370	1.7906	4.8926	4.9968	1.6138	0.78	0.78
Road 5, Road 4's Damping	6.7057	6.6573	5.2501	5.3388	1.4358	1.7911	4.8917	4.9968	1.6134	0.78	0.80
Road 5, Optimised Damping	**7.1083**	**7.7122**	**5.8339**	**5.8977**	1.4417	1.7914	4.8984	4.9969	1.6165	**0.82**	**0.76**
Average Front/Rear Damping Ratio's										**0.79**	**0.78**

‘Table 4-7’ shows the results of the random road 5 Degree of Freedom study. It shows a relationship between front and rear damping values, in the form of a ratio. These ratio’s show an average ratio of 0.775 between the front and rear suspension, interestingly this ratio is close to that of the ratio between static COG distance i.e. a/b = Ratio, 600/800 = 0.75. It can also be seen that over the random road profiles, the maximum grip is obtained when the front compression/rebound ratio is around the value of 1, and when comparing this to ‘Table 4-5’ it can be seen that it would allow the vehicle maintain good grip whilst traveling 45% quicker over the previous step profile, suggesting that the study should look into the effects of laying the random road profile over the step profile, so that a comparison of results can be established. It is clear that the random road profile requires different damping values to the smoothed step profile, in order to obtain maximum grip. Therefore, it can only be assumed that different damping would be needed for a random road with a step.

Table 4-8 - Random Road + Step Profile Grip Results

Random Road Comparisons											
Damping Description	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index	Front/Rear Comp Ratio	Front/Rear Rebound Ratio
Random Road 1											
Road 1, Optimised Damping	**8.3881**	**8.2184**	**6.4984**	**6.2818**	2.8628	3.5696	4.7969	4.9938	3.2162	**0.77**	**0.76**
Road 1, Road 2's Damping	6.4665	6.8240	4.9250	5.3329	2.8320	3.5467	4.7780	4.9936	3.1894	0.76	0.78
Road 1, Road 3's Damping	6.8591	6.7547	5.3166	5.2850	2.8369	3.5555	4.7803	4.9936	3.1962	0.78	0.78
Road 1, Road 4's Damping	6.7057	6.6573	5.2501	5.3388	2.8327	3.5554	4.7792	4.9936	3.1940	0.78	0.80
Road 1, Road 5's Damping	7.0694	7.6379	5.7749	6.0058	2.8518	3.5689	4.7873	4.9937	3.2103	0.82	0.79
Road+Step 1, Optimised Damping	**7.9536**	**8.6484**	**6.5009**	**6.2450**	2.8631	3.5697	4.7965	4.9938	3.2164	**0.82**	**0.72**
Road+Step 1, Road 2's Damping	6.5013	6.8181	5.1536	5.1695	2.8325	3.5501	4.7783	4.9936	3.1913	0.79	0.76
Road+Step 1, Road 3's Damping	6.9925	6.9040	5.4194	5.3246	2.8414	3.5578	4.7818	4.9936	3.1996	0.78	0.77
Road+Step 1, Road 4's Damping	6.5747	6.7839	5.2215	5.4102	2.8329	3.5559	4.7792	4.9936	3.1944	0.79	0.80
Road+Step 1, Road 5's Damping	7.0845	7.6885	5.9133	5.8328	2.8525	3.5695	4.7875	4.9937	3.2110	0.83	0.76

Random Road 2											
Road 2, Road 1's Damping	8.3881	8.2184	6.4984	6.2818	1.4317	1.7582	4.9243	4.9968	1.5950	0.77	0.76
Road 2 Optimised Damping	**6.4665**	**6.8240**	**4.9250**	**5.3329**	1.4384	1.7820	4.9113	4.9965	1.6102	**0.76**	**0.78**
Road 2, Road 3's Damping	6.8591	6.7547	5.3166	5.2850	1.4387	1.7815	4.9130	4.9965	1.6101	0.78	0.78
Road 2, Road 4's Damping	6.7057	6.6573	5.2501	5.3388	1.4382	1.7823	4.9122	4.9965	1.6102	0.78	0.80
Road 2, Road 5's Damping	7.0694	7.6379	5.7749	6.0058	1.4384	1.7737	4.9181	4.9967	1.6061	0.82	0.79
Road+Step 2, Road 1's Damping	7.9536	8.6484	6.5009	6.2450	1.4318	1.7585	4.9242	4.9968	1.5952	0.82	0.72
Road+Step 2 Optimised Damping	**6.5013**	**6.8181**	**5.1536**	**5.1695**	1.4384	1.7824	4.9116	4.9965	1.6104	**0.79**	**0.76**
Road+Step 2, Road 3's Damping	6.9925	6.9040	5.4194	5.3246	1.4390	1.7805	4.9141	4.9966	1.6097	0.78	0.77
Road+Step 2, Road 4's Damping	6.5747	6.7839	5.2215	5.4102	1.4383	1.7822	4.9123	4.9965	1.6102	0.79	0.80
Road+Step 2, Road 5's Damping	7.0845	7.6885	5.9133	5.8328	1.4383	1.7735	4.9183	4.9967	1.6059	0.83	0.76
Random Road 3											
Road 3, Road 1's Damping	8.3881	8.2184	6.4984	6.2818	1.4460	1.7759	4.9158	4.9970	1.6110	0.77	0.76
Road 3, Road 2's Damping	6.4665	6.8240	4.9250	5.3329	1.4466	1.7914	4.9039	4.9967	1.6190	0.76	0.78
Road 3, Optimised Damping	6.8591	6.7547	5.3166	5.2850	1.4483	1.7928	4.9052	4.9967	1.6206	**0.78**	**0.78**
Road 3, Road 4's Damping	6.7057	6.6573	5.2501	5.3388	1.4475	1.7933	4.9044	4.9967	1.6204	0.78	0.80
Road 3, Road 5's Damping	7.0694	7.6379	5.7749	6.0058	1.4490	1.7874	4.9098	4.9969	1.6182	0.82	0.79
Road+Step 3, Road 1's Damping	7.9536	8.6484	6.5009	6.2450	1.4457	1.7763	4.9157	4.9970	1.6110	0.82	0.72
Road +Step 3, Road 2's Damping	6.5013	6.8181	5.1536	5.1695	1.4467	1.7927	4.9041	4.9967	1.6197	0.79	0.76
Road+Step 3, Optimised Damping	6.9925	6.9040	5.4194	5.3246	1.4490	1.7923	4.9062	4.9967	1.6206	**0.78**	**0.77**
Road+Step 3, Road 4's Damping	6.5747	6.7839	5.2215	5.4102	1.4472	1.7931	4.9045	4.9967	1.6201	0.79	0.80
Road+Step 3, Road 5's Damping	7.0845	7.6885	5.9133	5.8328	1.4490	1.7873	4.9100	4.9969	1.6181	0.83	0.76

Random Road 4											
Road 4, Road 1's Damping	8.3881	8.2184	6.4984	6.2818	1.4339	1.7622	4.9204	4.9970	1.5980	0.77	0.76
Road 4, Road 2's Damping	6.4665	6.8240	4.9250	5.3329	1.4381	1.7813	4.9076	4.9967	1.6097	0.76	0.78
Road 4, Road 3's Damping	6.8591	6.7547	5.3166	5.2850	1.4387	1.7807	4.9091	4.9968	1.6097	0.78	0.78
Road 4, Optimised Damping	**6.7057**	**6.6573**	**5.2501**	**5.3388**	1.4381	1.7815	4.9083	4.9968	1.6098	**0.78**	**0.80**
Road 4, Road 5's Damping	7.0694	7.6379	5.7749	6.0058	1.4390	1.7747	4.9143	4.9969	1.6068	0.82	0.79
Road+Step 4, Road 1's Damping	7.9536	8.6484	6.5009	6.2450	1.4342	1.7623	4.9204	4.9970	1.5983	0.82	0.72
Road+Step 4, Road 2's Damping	6.5013	6.8181	5.1536	5.1695	1.4382	1.7811	4.9077	4.9967	1.6097	0.79	0.76
Road+Step 4, Road 3's Damping	6.9925	6.9040	5.4194	5.3246	1.4391	1.7799	4.9102	4.9968	1.6095	0.78	0.77
Road+Step 4, Optimised Damping	**6.5747**	**6.7839**	**5.2215**	**5.4102**	1.4381	1.7817	4.9084	4.9968	1.6099	**0.79**	**0.80**
Road+Step 4, Road 5's Damping	7.0845	7.6885	5.9133	5.8328	1.4390	1.7746	4.9144	4.9969	1.6068	0.83	0.76
Random Road 5											
Road 5, Road 1's Damping	8.3881	8.2184	6.4984	6.2818	1.4385	1.7828	4.9061	4.9971	1.6107	0.77	0.76
Road 5, Road 2's Damping	6.4665	6.8240	4.9250	5.3329	1.4336	1.7857	4.8928	4.9968	1.6097	0.76	0.78
Road 5, Road 3's Damping	6.8591	6.7547	5.3166	5.2850	1.4348	1.7875	4.8944	4.9969	1.6111	0.78	0.78
Road 5, Road 4's Damping	6.7057	6.6573	5.2501	5.3388	1.4335	1.7880	4.8935	4.9969	1.6107	0.78	0.80
Road 5, Optimised Damping	**7.1083**	**7.7122**	**5.8339**	**5.8977**	1.4393	1.7883	4.8999	4.9970	1.6138	**0.82**	**0.76**
Road+Step 5, Road 1's Damping	7.9536	8.6484	6.5009	6.2450	1.4392	1.7830	4.9061	4.9971	1.6111	0.82	0.72
Road+Step 5, Road 2's Damping	6.5013	6.8181	5.1536	5.1695	1.4337	1.7863	4.8929	4.9969	1.6100	0.79	0.76
Road+Step 5, Road 3's Damping	6.9925	6.9040	5.4194	5.3246	1.4361	1.7876	4.8956	4.9969	1.6118	0.78	0.77
Road+Step 5, Road 4's Damping	6.5747	6.7839	5.2215	5.4102	1.4338	1.7882	4.8936	4.9969	1.6110	0.79	0.80
Road 5, Optimised Damping	**7.0845**	**7.6885**	**5.9133**	**5.8328**	1.4392	1.7884	4.8998	4.9970	1.6138	**0.83**	**0.76**
Average Front/Rear Damping Ratio's										**0.80**	**0.76**

‘Table 4-8’ shows a slight variation between the results of the random road damping values and that of the random road + step profile damping values. At the base step duration of 0.2s it can be seen that if the compression is reduced slightly, and rebound is increased slightly, then the grip index is able to supersede that of the optimised values of the random road. However, if the damping is optimised in the reverse order, compression is increased rebound is reduced (as shown for random road 5), the optimised grip only maintains that of the previous damping values and there are no great grip gains to be made. Therefore, it could be stated that within a suspension algorithm, that if a step is approached that the compression should be reduced and the rebound increased in order to maintain grip. However, in order to confirm this, a study on a single road profile (Road Profile 2) with an increasing step shall be completed in the same manner as the previous step profile studies shown in section ‘4.8.2 5 Degree of Freedom Finalised Step Profile Grip Study’ of this report.

4.8.5 5 Degree of Freedom Random Road + Step Speed Increase

Within this section of the report the step duration will be increased over a given random road profile, to determine if the statement, “if a step is approached that the compression should be reduced and the rebound increased in order to maintain grip”, made in section ‘4.8.4 5 Degree of Freedom Random Road Profile Grip Study’ is accurate.

Table 4-9 - Random Road 2 + Step Profile - Active Damping with Speed Increase

Random Road Comparisons + Step Increasing Speed, ACTIVE DAMPING												
Speed Increase (%)	Damping Description	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index	Front/Rear Comp Ratio	Front/Rear Rebound Ratio
Random Road 2												
0	Road 2 Optimised Damping	6.824	6.466	5.333	4.925	1.438	1.782	4.911	4.996	1.610	0.78	0.76
6.25	Road 2 Optimised Damping	6.824	6.466	5.333	4.925	1.438	1.781	4.912	4.996	1.609	0.78	0.76
12.5	Road 2 Optimised Damping	6.824	6.466	5.333	4.925	1.438	1.779	4.912	4.997	1.609	0.78	0.76
18.75	Road 2 Optimised Damping	6.824	6.466	5.333	4.925	1.438	1.779	4.913	4.997	1.608	0.78	0.76
25	Road 2 Optimised Damping	6.824	6.466	5.333	4.925	1.435	1.767	4.915	4.997	1.601	0.78	0.76
31.25	Road 2 Optimised Damping	6.824	6.466	5.333	4.925	1.432	1.747	4.918	4.997	1.590	0.78	0.76
37.5	Road 2 Optimised Damping	6.864	6.419	5.311	4.933	1.432	1.747	4.918	4.997	1.590	0.78	0.7
43.75	Road 2 Optimised Damping	6.668	6.374	5.323	4.960	1.428	1.767	4.916	4.997	1.597	0.80	0.78
50	Road 2 Optimised Damping	6.668	6.374	5.323	49.60	1.418	1.727	4.926	4.997	1.572	0.80	0.78
56.25	Road 2 Optimised Damping	7.473	7.094	4.174	5.495	1.415	1.740	4.924	4.997	1.578	0.56	0.77
62.5	Road 2 Optimised Damping	7.473	7.094	4.174	5.495	1.411	1.753	4.923	4.997	1.582	0.56	0.77
68.75	Road 2 Optimised Damping	7.473	7.094	4.174	5.495	1.406	1.744	4.924	4.997	1.575	0.56	0.77
75	Road 2 Optimised Damping	6.581	6.915	4.728	5.439	1.399	1.744	4.925	4.997	1.571	0.72	0.79
81.25	Road 2 Optimised Damping	4.937	6.066	4.346	5.934	1.383	1.706	4.922	4.997	1.544	0.88	0.98
87.5	Road 2 Optimised Damping	6.299	8.048	4.803	5.752	1.376	1.685	4.931	4.998	1.531	0.76	0.71
93.75	Road 2 Optimised Damping	6.896	7.029	7.509	8.032	1.356	1.547	4.941	4.998	1.451	1.09	1.14
100	Road 2 Optimised Damping	6.273	7.144	6.354	7.628	1.331	1.487	4.944	4.998	1.409	1.01	1.07
	Averages	6.738	6.732	5.190	5.510	1.410	1.722	4.922	4.997	1.566	0.78	0.82

‘Table 4-9’ shows the results of increasing the step duration over the random road profile. Interestingly the ratio between front and rear damping for both compression and rebound increase as the vehicle increases its speed. Therefore, the previous statement was only correct for traveling up to a 50% vehicle speed increase. Thus, it provided useful to take the average damping values and perform a short study of the results with the average active damping values, to determine the variation of the grip indexes.

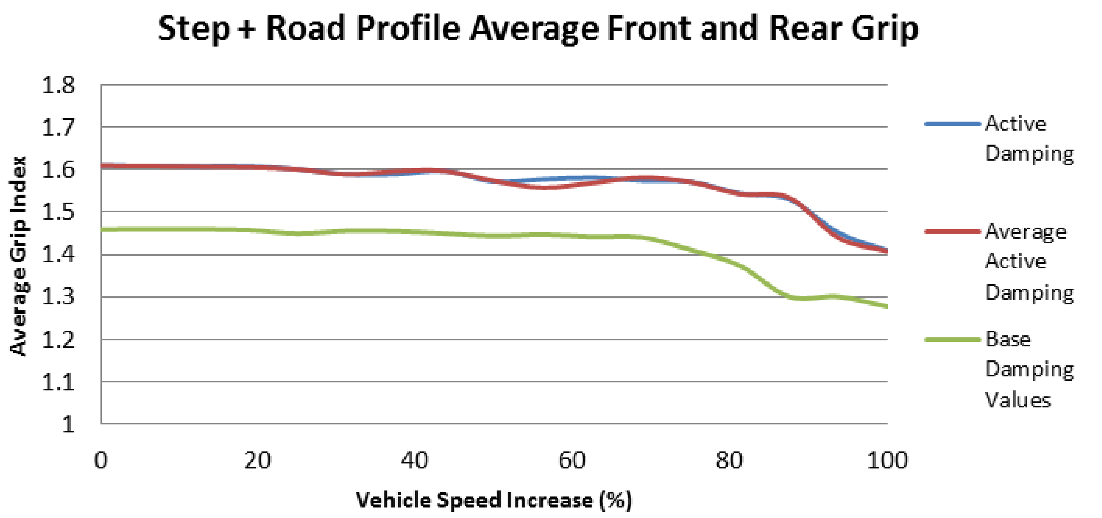

Figure 4-60 - Step + Road, Increasing Speed Grip Results

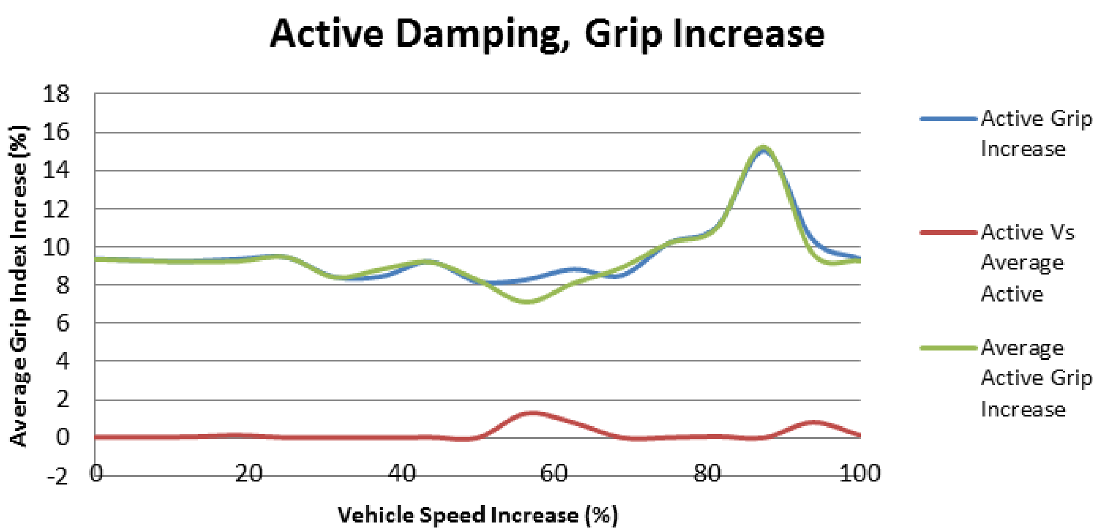

Figure 4-61 - Step + Road, Grip Increase Comparison

Table 4-10 - Step + Road, Increasing Speed Active Damping Grip Results

Random Road Comparisons + Step, AVERAGE ACTIVE DAMPING												
Speed Increase (%)	Damping Description	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index	Front/Rear Comp Ratio	Front/Rear Rebound Ratio
Random Road 2												
0	Road 2 Optimised Damping	6.738	6.732	5.910	5.510	1.438	1.781	4.913	4.997	1.610	0.82	0.77
6.25	Road 2 Optimised Damping	6.738	6.732	5.910	5.510	1.438	1.780	4.913	4.997	1.609	0.82	0.77
12.5	Road 2 Optimised Damping	6.738	6.732	5.910	5.510	1.438	1.778	4.913	4.997	1.608	0.82	0.77
18.75	Road 2 Optimised Damping	6.738	6.732	5.910	5.510	1.437	1.775	4.914	4.997	1.606	0.82	0.77
25	Road 2 Optimised Damping	6.738	6.732	5.910	5.510	1.435	1.768	4.916	4.997	1.601	0.82	0.77
31.25	Road 2 Optimised Damping	6.738	6.732	5.910	5.510	1.432	1.747	4.919	4.997	1.590	0.82	0.77
37.5	Road 2 Optimised Damping	6.738	6.732	5.910	5.510	1.429	1.764	4.918	4.997	1.596	0.82	0.77
43.75	Road 2 Optimised Damping	6.738	6.732	5.910	5.510	1.425	1.769	4.919	4.997	1.597	0.82	0.77
50	Road 2 Optimised Damping	6.738	6.732	5.910	5.510	1.417	1.730	4.927	4.997	1.574	0.82	0.77
56.25	Road 2 Optimised Damping	6.738	6.732	5.910	5.510	1.414	1.702	4.929	4.998	1.558	0.82	0.77
62.5	Road 2 Optimised Damping	6.738	6.732	5.910	5.510	1.413	1.725	4.926	4.998	1.569	0.82	0.77
68.75	Road 2 Optimised Damping	6.738	6.732	5.910	5.510	1.407	1.756	4.923	4.997	1.582	0.82	0.77
75	Road 2 Optimised Damping	6.738	6.732	5.910	5.510	1.398	1.744	4.926	4.997	1.571	0.82	0.77
81.25	Road 2 Optimised Damping	6.738	6.732	5.910	5.510	1.389	1.697	4.930	4.997	1.543	0.82	0.77
87.5	Road 2 Optimised Damping	6.738	6.732	5.910	5.510	1.379	1.690	4.930	4.998	1.534	0.82	0.77
93.75	Road 2 Optimised Damping	6.738	6.732	5.910	5.510	1.357	1.522	4.941	4.998	1.440	0.82	0.77
100	Road 2 Optimised Damping	6.738	6.732	5.910	5.510	1.333	1.483	4.943	4.998	1.408	0.82	0.77
Averages						1.4106	1.7184	4.9236	4.9973	1.5645		

From analysing 'Figure 4-60, Figure 4-61 and Table 4-10', it can be seen that there is significant grip gains to be made from using the active damping. However, it does show that when the average active damping values are used i.e. fixed compression and rebound values, the grip gains stay fairly high and difference between active damping and the fixed average active damping values, is only a maximum of 1.5%. Therefore, this suggests that there is a so called 'sweet spot' for the damping, and it is very possible that the sweet spot for this vehicle is the given damping values within 'Table 4-10'. However, so far within the report the vehicle has only been analysed when traveling over a ground profile, and no alternative inputs have been given. Therefore, it is appropriate to now study the effects of braking within the system.

4.8.6 5 Degree of Freedom Braking

Within this section of the report, the 5 Degree of Freedom model will be set to brake at various pressures over random road profile 2, to determine whether the grip indexes can be improved. It can be assumed that during braking the grip index will be increased due to the fact that the tyre is being pushed into the road and held in place, rather than being able to oscillate and overshoot. The braking will be simulated similar to a step profile and will be measured in 'Bar'. The equation given in section '4.7.2 - 5 Degree of Freedom Model Formulation' states the equation that converts this brake pressure (Bar) to a force acting on the vehicle. The braking has been set to ramp in to full pressure by 0.75 seconds, to maintain that pressure for 1.25 seconds and to release the brake gradually (trailing effect) for 1.5 seconds. Therefore, the entire simulated braking procedure will only take 3.5 seconds, regardless of the braking force.

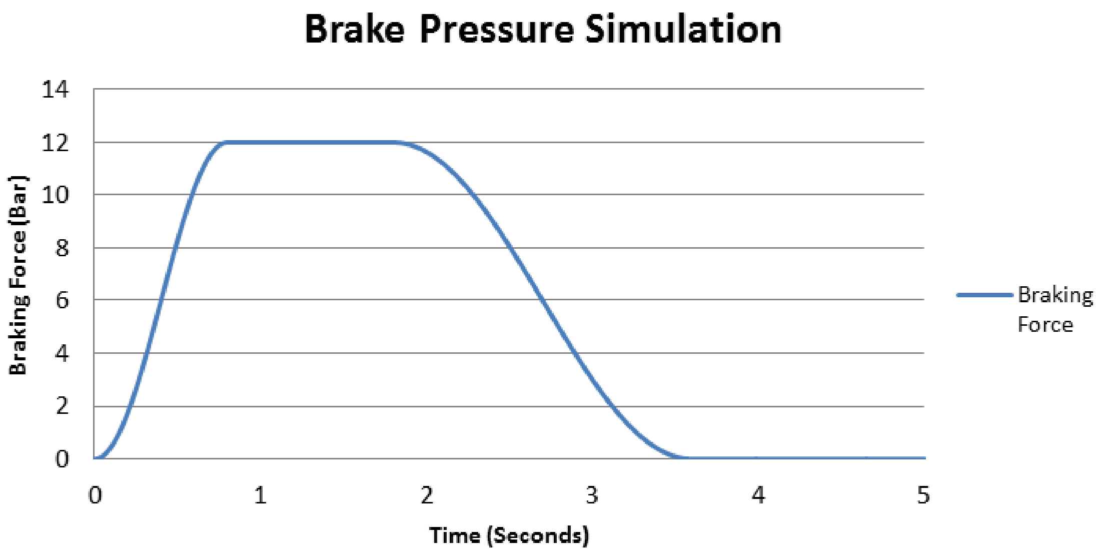

Figure 4-62 - Brake Pressure Simulation

4.8.6.1 6 Bar of Brake Pressure

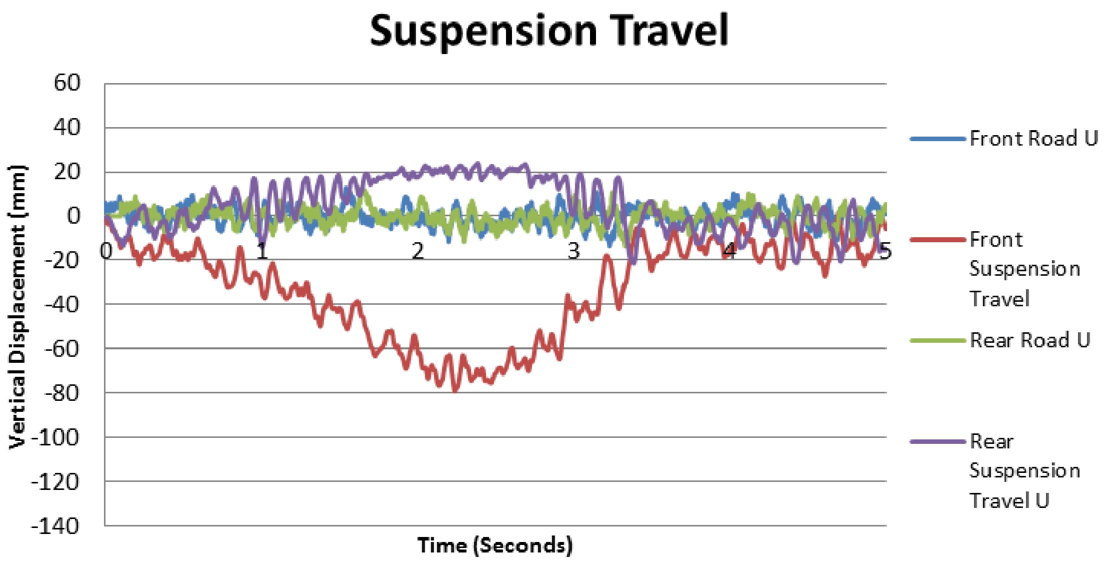

Figure 4-63 - Base Damping Values at 6 Bar of Braking, Suspension Travel

'Figure 4-63' shows the effects of 6 Bar of braking on the 5 Degree of Freedom model with the base damping values. As you can see the front suspension dives by just less than 80mm, the indexes obtained can be seen below in 'Table 4-11'.

Table 4-11 - 6 Bar of Braking Grip Indexes

Damping Description	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Random Road 2, 6 Bar of Braking Pressure									
Road 2, Base Damping Values	2.50	3.00	2.50	3.00	1.245	1.630	4.919	4.998	1.437
Road 2, 6 Bar Optimised	6.74	6.49	5.00	5.23	1.438	1.678	4.931	4.998	1.558

From 'Table 4-10' it can be seen that an average 'Average Grip Index' of 1.565 can be obtained with different damping values without braking forces, which is less than that of the 'Average Grip Index' with the Base damping values whilst braking. Therefore, through running Microsoft Excel's solver, a better 'Average Grip Index' of 1.558 was obtained, and that the results show very different damping values. It can also be noted that the damping is similar to that of the average of the results over a stepped road profile in 'Table 4-9'. 'Table 4-11' currently states that the grip has been reduced from braking. Therefore, the assumption that braking would provide increased grip was incorrect and even though the tyre is being forced into the ground, it provides larger forces acting through the tyre to create increased tyre wear. Therefore, we can now assume that the grip will depreciate as the brake pressure is increase, similar to that of a real life scenario.

4.8.6.2 8 Bar of Brake Pressure

Table 4-12 - 8 Bar of Braking Grip Indexes

Damping Description	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Random Road 2, 8 Bar of Braking Pressure									
Road 2, Base Damping Values	2.50	3.00	2.50	3.00	1.236	1.584	4.922	4.998	1.410
Road 2, 6 Bar Optimised	6.74	6.49	5.00	5.23	1.437	1.664	4.932	4.998	1.551
Road 2, 8 Bar Optimised	6.79	6.61	5.21	5.45	1.438	1.667	4.932	4.998	1.553

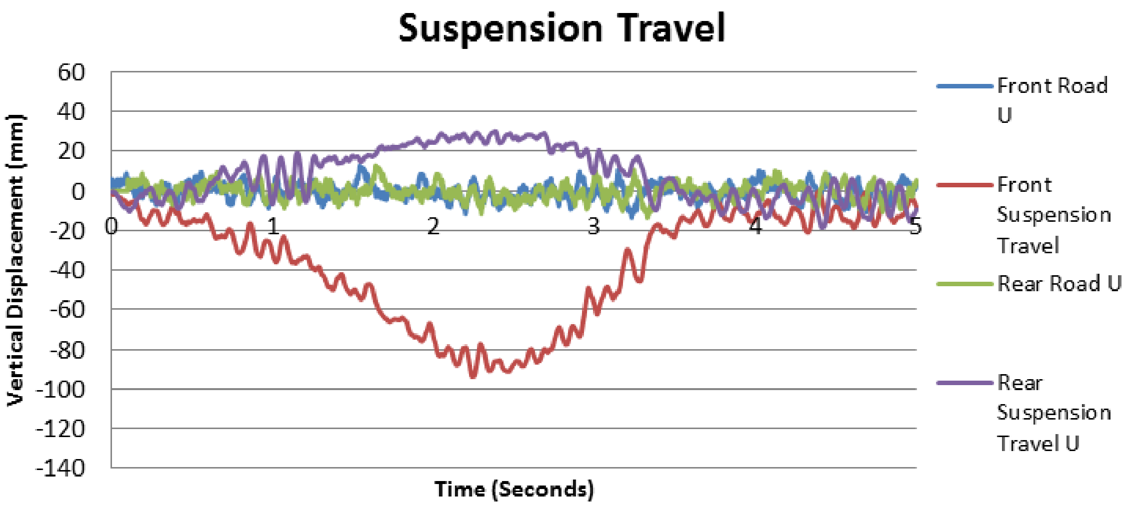

Figure 4-64 - Optimised Damping Values at 8 Bar, Suspension Travel

'Figure 4-64' shows that at 8 Bar of braking pressure, the front suspension dives to around 90mm. However, it is interesting to note that if you optimise the grip index with Microsoft Excel's solver, so that front and rear grip is optimised, then the amount the front suspension travels, stays the approximately the same, regardless of the damping. However, if only the front compression is increased or decreased then the vehicle will move more or less accordingly. Therefore, the suspension travel is the same (approximately) for the base damping values to that of the optimised damping values when 8 Bar of braking pressure is applied. From 'Table 4-12' it can be seen that as the braking pressure has been increased, so has all of the damping, I.e. front compression, front rebound, rear compression and rear rebound.

4.8.6.3 10 Bar of Braking Pressure

Table 4-13 - 10 Bar of Braking Grip Indexes

Damping Description	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Random Road 2, 10 Bar of Braking Pressure									
Road 2, Base Damping Values	2.50	3.00	2.50	3.00	1.234	1.571	4.925	4.998	1.403
Road 2, 6 Bar Optimised	6.74	6.49	5.00	5.23	1.432	1.639	4.933	4.998	1.535
Road 2, 8 Bar Optimised	6.79	6.61	5.21	5.45	1.432	1.641	4.933	4.998	1.537
Road 2, 10 Bar Optimised	7.21	6.96	6.49	5.03	1.439	1.657	4.933	4.998	1.548

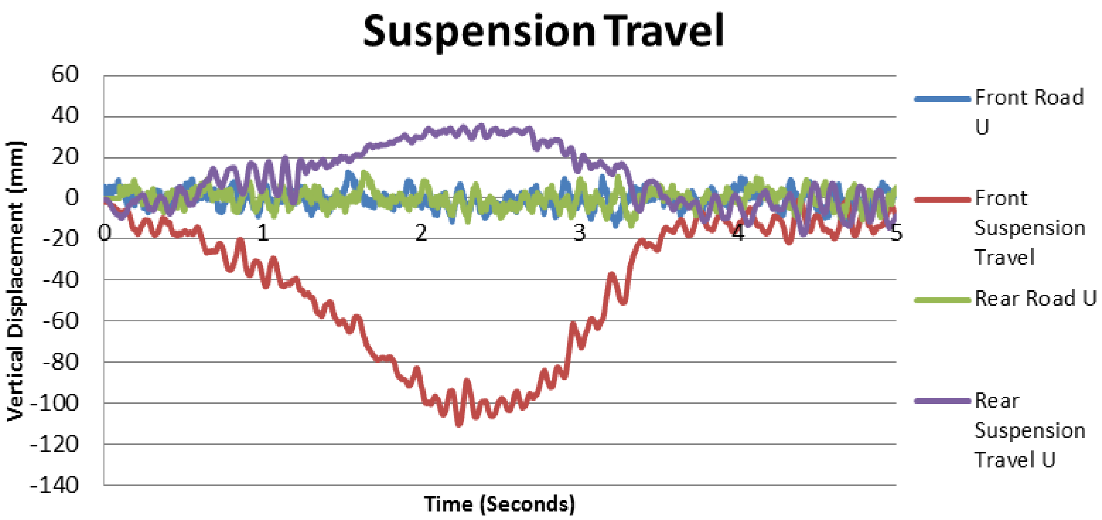

Figure 4-65 - Optimised Damping Values at 10 Bar, Suspension Travel

‘Figure 4-65’ shows that at 10 Bar of braking pressure, the front suspension dives to around 100mm. From ‘Table 4-13’ it can be seen that all the damping has been increased apart from the rear rebound which has been decreased by the same amount that the front compression has been increased.

4.8.6.4 12 Bar of Braking Pressure

Table 4-14 - 12 Bar of Braking Grip Indexes

Damping Description	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Random Road 2, 12 Bar of Braking Pressure									
Road 2, Base Damping Values	2.50	3.00	2.50	3.00	1.238	1.573	4.925	4.998	1.405
Road 2, 6 Bar Optimised	6.74	6.49	5.00	5.23	1.422	1.665	4.932	4.998	1.544
Road 2, 8 Bar Optimised	6.79	6.61	5.21	5.45	1.422	1.666	4.933	4.998	1.544
Road 2, 10 Bar Optimised	7.21	6.96	6.49	5.03	1.420	1.646	4.935	4.998	1.533
Road 2, 12 Bar Optimised	6.99	6.55	5.64	5.45	1.422	1.679	4.932	4.998	1.551

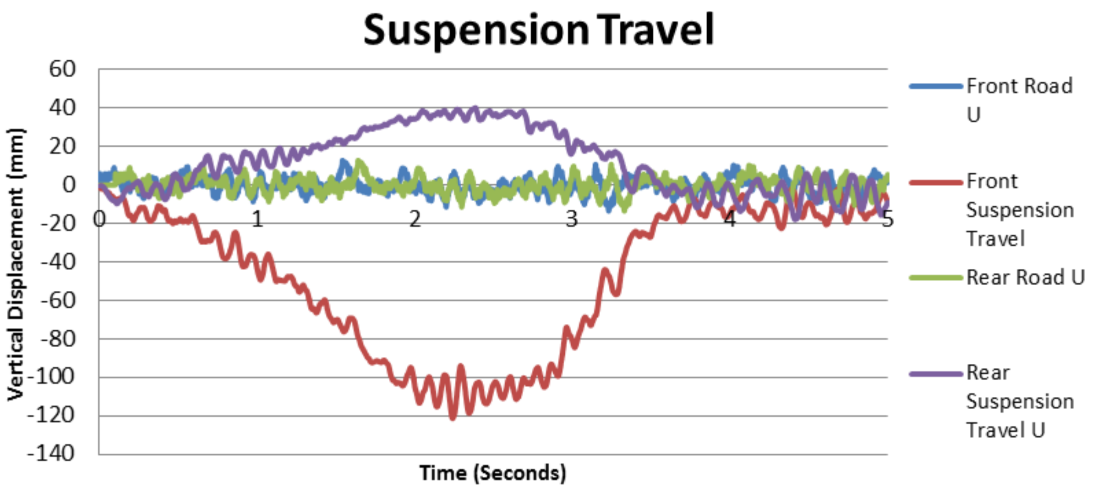

Figure 4-66 - Optimised Damping Values at 12 Bar, Suspension Travel

'Figure 4-66' shows that at 12 Bar of braking pressure, the front suspension dives to around 110mm. Therefore, with the given vehicle parameters on average the front suspension will dive 5mm/Bar of brake pressure. 'Table 4-14' shows that there is no real relationship between the brake pressure and the required damping to maintain a higher 'Average Grip Index'. However, this study has optimised the 'Average Grip Index' and it can be noted that during braking the maximum grip is required at the front wheel. This is because, the rear wheel is virtually in the air and the rear grip is not required for braking. Therefore, through running the study again, by optimising the 'Front Grip Index' rather than both grip indexes, a pattern should be found.

4.8.7 5 Degree of Freedom Braking, Front Optimisation

Within this section of the report the previous braking study will be re-completed by only optimising the 'Front Grip Index'. However, all the damping values will still be adjusted to optimise the 'Front Grip Index'.

Table 4-15 - 'Front Grip Index' Optimised, All Damping Adjustment

Damping Description	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Random Road 2									
Road 2, 6 Bar Optimised	7.60	7.08	5.47	6.52	1.442	1.656	4.933	4.998	1.549
Road 2, 8 Bar Optimised	7.65	6.98	8.74	3.51	1.444	1.597	4.933	4.998	1.520
Road 2, 10 Bar Optimised	7.60	6.96	8.73	3.49	1.437	1.589	4.934	4.998	1.513
Road 2, 12 Bar Optimised	7.24	6.54	4.94	5.80	1.423	1.658	4.934	4.998	1.541

'Table 4-15' shows the results of the optimised damping values at the corresponding brake pressures against the grip indexes. It can be seen that there is still little to none relationship between the damping and the brake pressure. Therefore, the average of the rear damping values from the previous section (4.8.6 5 Degree of Freedom Braking) will be used for the rear. This will enable the modification to only the front compression and rebound to optimise the 'Front Grip Index', the study will also look at the optimised damping values when braking from 0 bar to 14 bar of brake pressure to find a relationship between damping and brake pressure in the form of a graph, so that a lookup table can be created.

4.8.7.1 Varying Braking Pressure

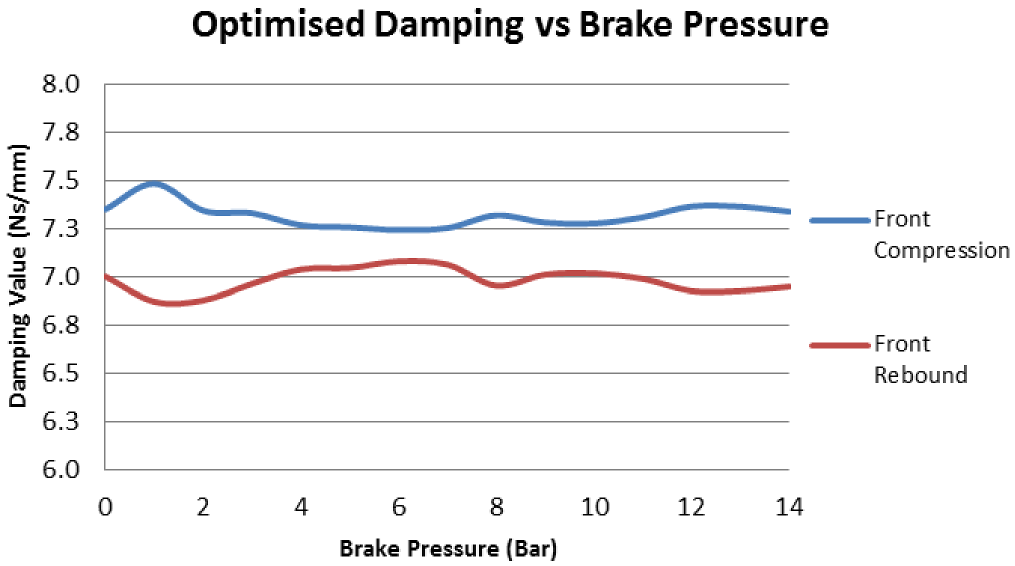

Figure 4-67 - Optimised Damping vs. Brake Pressure, Random Road 2

Table 4-16 - Optimised Damping at Multiple Brake Pressures, Random Road 2

Road Profile	Brake Pressure	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Random Road 2, Braking Pressure										
Road 2	0	7.352	7.002	5.190	5.510	1.441	1.779	4.915	4.996	1.610
Road 2	1	7.485	6.873	5.190	5.510	1.441	1.779	4.915	4.996	1.610
Road 2	2	7.344	6.879	5.190	5.510	1.441	1.780	4.914	4.996	1.610
Road 2	3	7.331	6.965	5.190	5.510	1.441	1.779	4.914	4.996	1.610
Road 2	4	7.269	7.039	5.190	5.510	1.441	1.779	4.915	4.996	1.610
Road 2	5	7.258	7.047	5.190	5.510	1.441	1.779	4.915	4.996	1.610
Road 2	6	7.244	7.081	5.190	5.510	1.441	1.779	4.915	4.996	1.610
Road 2	7	7.254	7.064	5.190	5.510	1.441	1.780	4.915	4.996	1.610
Road 2	8	7.320	6.955	5.190	5.510	1.441	1.780	4.914	4.996	1.610
Road 2	9	7.282	7.012	5.190	5.510	1.441	1.780	4.914	4.996	1.610
Road 2	10	7.277	7.019	5.190	5.510	1.441	1.780	4.914	4.996	1.610
Road 2	11	7.310	6.990	5.190	5.510	1.441	1.780	4.914	4.996	1.610
Road 2	12	7.367	6.927	5.190	5.510	1.441	1.780	4.914	4.996	1.611
Road 2	13	7.366	6.928	5.190	5.510	1.441	1.780	4.914	4.996	1.611
Road 2	14	7.339	6.950	5.190	5.510	1.441	1.780	4.914	4.996	1.611

'Table 4-16' and 'Figure 4-67' both show that there is a very small difference in the damping required to maintain a maximum 'Front Grip Index'. Therefore, due to the larger variation in the grip index results from 'Table 4-15' the study shall be repeated with the both the front and rear compression and rebound being adjusted. However, it is interesting to note that the compression and rebound are very close to mirroring each other in ‘Figure 4-67’ i.e. as one value increases the other decreases by a similar amount.

4.8.7.2 Varying Brake Pressure, Front Optimisation, Fully Adjusted Damping

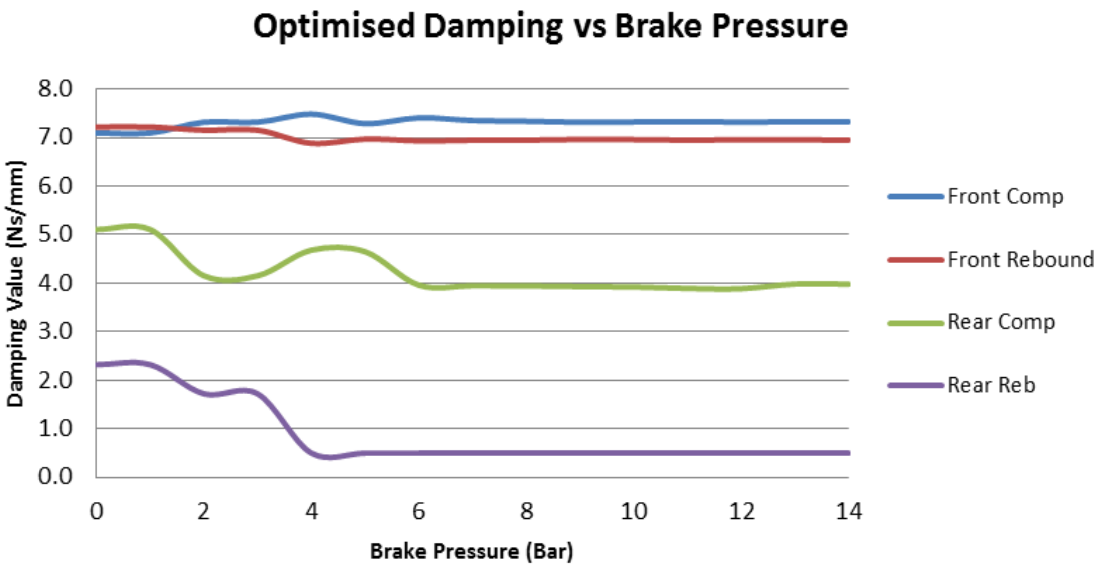

Figure 4-68 - Optimised Front & Rear Damping vs. Brake Pressure, Random Road 2

Table 4-17- Optimised Front & Rear Damping at Multiple Brake Pressures, Random Road 2

Road Profile	Brake Pressure	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Random Road 2, Braking Pressure										
Road 2	0	7.096	7.218	5.107	2.322	1.4432	1.719	4.908	4.996	1.581
Road 2	1	7.096	7.218	5.107	2.322	1.4432	1.718	4.908	4.996	1.581
Road 2	2	7.318	7.152	4.153	1.721	1.4439	1.655	4.906	4.996	1.550
Road 2	3	7.318	7.152	4.153	1.721	1.4440	1.655	4.906	4.996	1.549
Road 2	4	7.484	6.883	4.682	0.500	1.4442	1.486	4.905	4.996	1.465
Road 2	5	7.288	6.970	4.649	0.500	1.4443	1.485	4.904	4.996	1.465
Road 2	6	7.407	6.933	3.960	0.500	1.4445	1.459	4.903	4.996	1.452
Road 2	7	7.352	6.946	3.948	0.500	1.4443	1.459	4.904	4.996	1.452
Road 2	8	7.336	6.948	3.944	0.500	1.4442	1.459	4.904	4.996	1.452
Road 2	9	7.316	6.962	3.930	0.500	1.4443	1.460	4.904	4.996	1.452
Road 2	10	7.323	6.959	3.921	0.500	1.4443	1.460	4.904	4.996	1.452
Road 2	11	7.326	6.947	3.892	0.500	1.4443	1.457	4.904	4.996	1.450
Road 2	12	7.320	6.955	3.887	0.500	1.4442	1.456	4.904	4.996	1.450
Road 2	13	7.324	6.953	3.984	0.500	1.4442	1.463	4.904	4.996	1.454
Road 2	14	7.327	6.950	3.979	0.500	1.4442	1.462	4.904	4.996	1.453

‘Figure 4-68 and Table 4-17’ show that as the brake pressure is increased that the rear rebound damping is reduced to minimum damping so that the ‘Front Grip Index’ can maintain a higher level of grip. From ‘Figure 4-68’ it can be seen that the front compression is increased slightly by approximately 0.3 Ns/mm and the front rebound is decreased by approximately the same amount when the brakes increase past 3 Bar. From the table it can be seen that the front damping does not change much in comparison to the rear. However, once the rear rebound has been reduced as far as 0.5Ns/mm the rear compression remains around 3.9Ns/mm to optimise the ‘Front Grip Index’. It can be noted that the index only varies by 0.0001 which, arguably, is a small amount. However, the fact that it is maintaining the grip is the ‘key’ result of the study, as the rider can push the brakes and if the active suspension uses the damping given in ‘Table 4-17’ then the vehicle would still maintain its grip. Therefore, the suspension has been greatly improved rather than a given setup which typically, the ‘Front Grip Index’ would reduce as the rider broke more (used a larger braking force). From the results given in ‘Table 4-17’ it is clear that when optimising any of the grip indexes, that the all damping values should be adjusted to maintain the maximum grip in any specific area, i.e. adjust both front and rear damping to optimise either front or rear grip indexes.

4.8.8 5 Degree of Freedom Banking

Within this section of the report the model will be put through six banking procedures, each procedure will take the same time to reach the given bank angle and return to the vertical position. The vehicle model will be analysed at 0, 10, 20, 30, 40 and 50 degrees of bank angle and Microsoft Excel's solver will be used to determine the optimum damping values to maintain a maximum 'Average Grip Index'. 'Figure 4-69' shows the profile of how each banking procedure will be performed, with 0 degrees representing the vertical position of the vehicle. Therefore, this graph shows a minimum angle of 40 degrees between the ground and the centre line of the vehicle at 2.5 seconds. The study represents the vehicle going around a corner without the implementation of the brakes. Thus, the 'Average Grip Index' is to be optimised, rather than just the front grip.

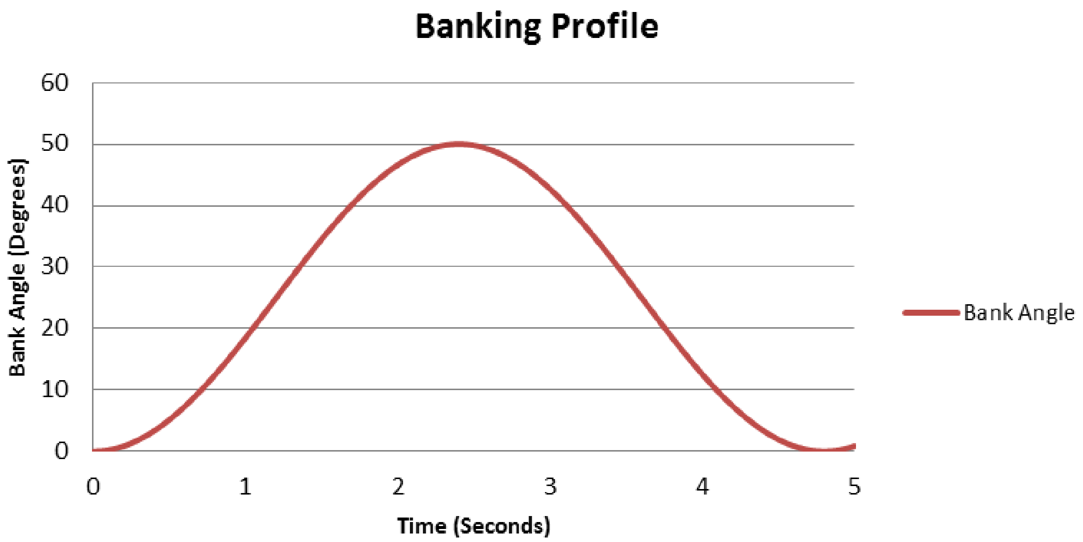

Figure 4-69 - Banking Profile Graph

Table 4-18 - Banking Grip Results

Road Profile	Bank Angle	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Random Road 2, Bank Angle										
Road 2	0	6.834	6.397	5.334	4.926	1.4399	1.784	4.910	4.996	1.612
Road 2	10	6.813	6.381	5.306	4.940	1.4450	1.790	4.910	4.996	1.618
Road 2	20	6.766	6.374	5.300	4.831	1.4606	1.809	4.908	4.996	1.635
Road 2	30	6.699	6.349	5.183	4.836	1.4865	1.839	4.906	4.996	1.663
Road 2	40	6.619	6.331	5.054	4.829	1.5232	1.882	4.902	4.996	1.703
Road 2	50	6.572	6.333	4.975	4.820	1.5705	1.938	4.896	4.996	1.754

‘Table 4-18’ shows the optimised damping values over road profile 2 for five different lean angles. The table shows that as the bank angle is increased; all the damping values are decreased in order to maintain the maximum ‘Average Grip Index’. It can also be noted that as the bank angle increases, all the grip increases accordingly.

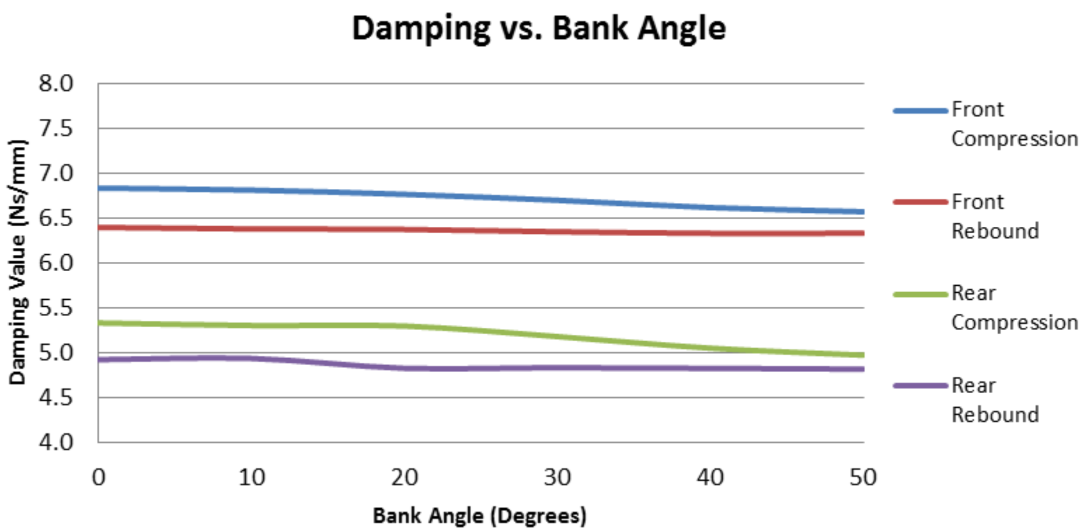

Figure 4-70 - Damping Values vs. Bank Angle Graph

‘Figure 4-70’ shows that the main factors of grip lie within the front and rear compression as these are the values that vary more. It can be noted the depreciation of compression is only small. However, the results of the report so far have shown that when looking for increased grip performance from an initially optimised value, that it usually only requires a small adjustment to either maintain that high grip or to better the previous grip. Next the report will study the effects of braking and banking as a rider will usually brake prior to the corner and then bank into the corner. However, it is extremely common for a motorcycle rider to ‘trail’ the brake; this is where the rider holds the brake on slightly within the corner.

4.8.9 5 Degree of Freedom Banking and Braking

Within this section of the report the vehicle model will be put through the same banking procedures as the previous section. However, at each banking procedure, the vehicle will also be put through each braking scenario, and the damping values from the previous section will be adjusted by the same amount as the braking scenarios in section '4.8.7.2 - Varying Brake Pressure, Front Optimisation, Fully Adjusted Damping', in order to optimise the 'Front Grip Index'. 'Figure 4-71' shows the profile in which both the braking and banking will be implemented, it can be seen that the braking overlaps the banking procedure; this represents the rider trailing the brake into the corner. The figure only shows the maximum baking pressure and banking angle. However, the duration in which the process takes will not change at lower brake pressures and reduced bank angles.

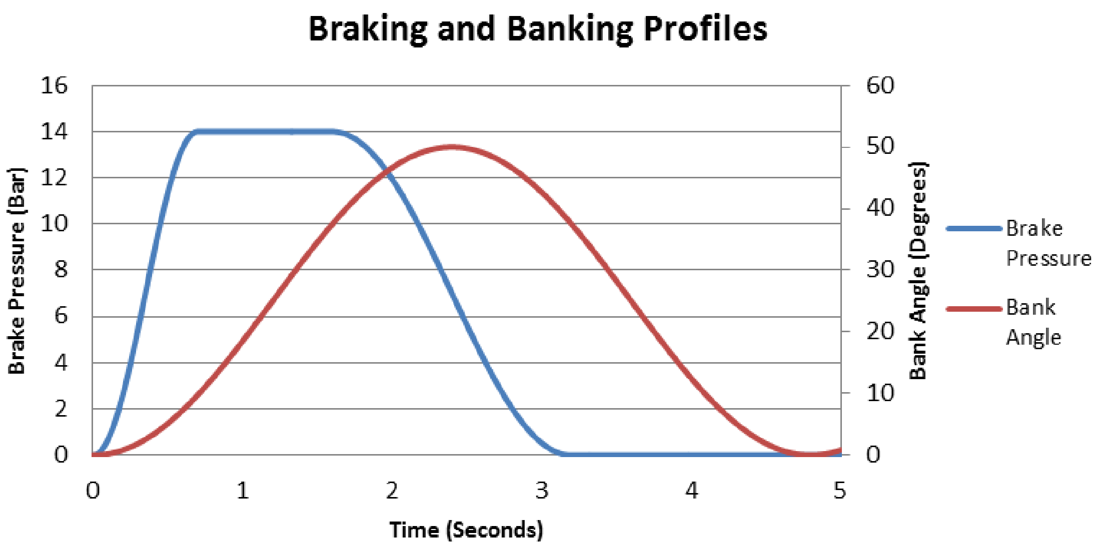

Figure 4-71 - Braking and Banking Profiles - Maximum Values

Table 4-19 - Damping Adjustment Due to Brake Pressure

Road Profile	Brake Pressure	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)
		Change in	Change in	Change in	Change in
Random Road 2, Braking Pressure					
Road 2	0	0.000	0.000	0.000	0.000
Road 2	1	0.000	0.000	0.000	0.000
Road 2	2	0.222	-0.066	-0.954	-0.601
Road 2	3	0.000	0.000	0.000	0.000
Road 2	4	0.166	-0.270	0.529	-1.221
Road 2	5	-0.196	0.088	-0.033	0.000
Road 2	6	0.119	-0.037	-0.689	0.000
Road 2	7	-0.055	0.013	-0.012	0.000
Road 2	8	-0.016	0.002	-0.004	0.000
Road 2	9	-0.020	0.015	-0.014	0.000
Road 2	10	0.006	-0.003	-0.010	0.000
Road 2	11	0.004	-0.011	-0.029	0.000
Road 2	12	-0.007	0.008	-0.005	0.000
Road 2	13	0.004	-0.003	0.097	0.000
Road 2	14	0.004	-0.003	-0.005	0.000

The results given in ‘Table 4-19’ show amount each damping value was varied to optimise the ‘Front Grip Index’ per brake pressure , the damping adjustments can be put into the optimised damping values of the bank angle study to determine the optimised front grip when banking and braking.

From adding the results in ‘Table 4-19’ to the results of ‘Table 4-18’, the following graphs were produced.

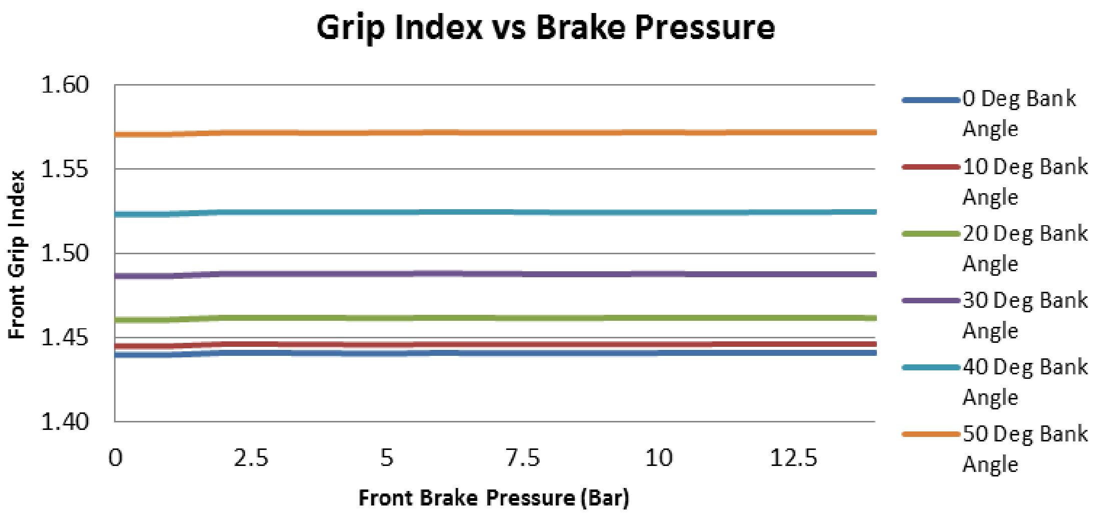

Figure 4-72 - Front Grip Whilst Banking vs. Brake Pressure

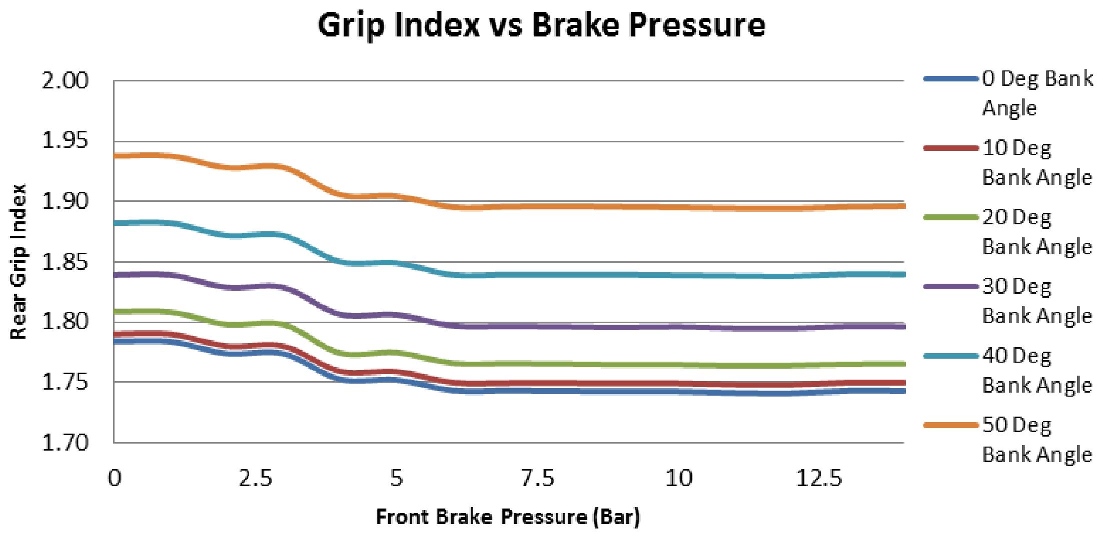

Figure 4-73 - Rear Grip Whilst Banking vs. Brake Pressure

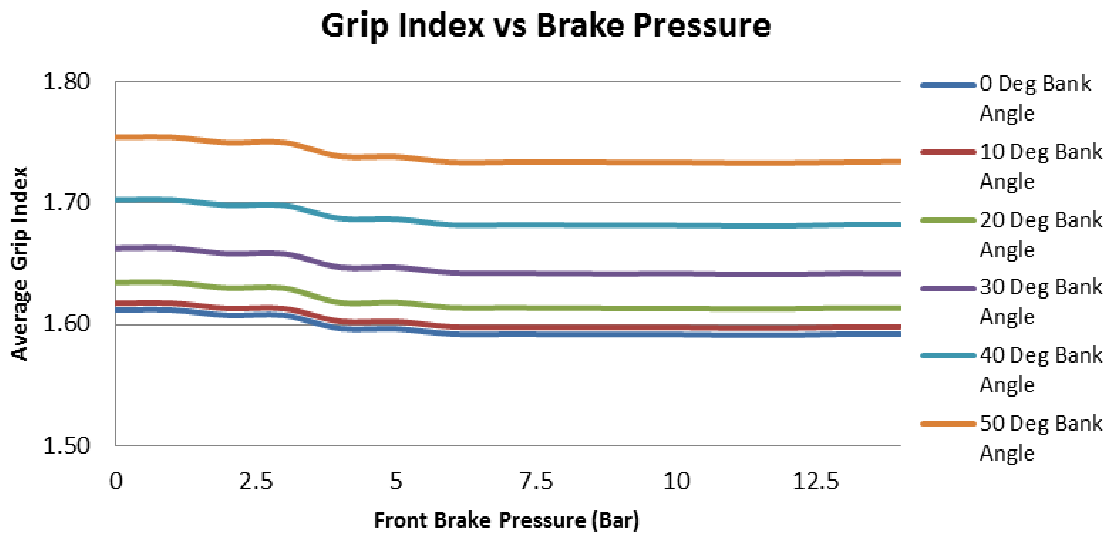

Figure 4-74 - Average Grip Whilst Banking vs. Brake Pressure

From 'Figure 4-72, Figure 4-73 and Figure 4-74' it can be seen that in order to maintain the high 'Front Grip Index' whilst braking and banking, that the 'Rear Grip Index' is reduced. However, this is expected as the optimisation for the braking was for the 'Front Grip Index' and the study shown in section '4.8.7.2 - Varying Brake Pressure, Front Optimisation, Fully Adjusted Damping' where the 'Front Grip Index' was optimised, the 'Rear Grip Index' was reduced. However, it can be noted that the 'Rear Grip Index' maintains a higher grip value than the front at all times. This could be due to the geometry of the bike, where more weight is over the front than the rear so that the vehicle naturally over works the front tyre and reduces grip. The full table of results for the banking and braking graphs within this section can be found in 'APPENDIX B – Braking & Banking Results'

4.9 5 Degree of Freedom, Damper Delay Rates

Within this section of the report the damper delay rates will be analysed. Therefore, the speed in which the damper responds to the movement of the wheels will be reduced to determine the effects on grip. This delay rate represents the reaction speed of damper. This is the rate in which the damper will change direction between compression and rebound, and the response speed to an excitation at the wheel, essentially, the movement created by the wheel will move the suspension slightly before the damper actually dampens the force. This is accomplished by making the damper force equation look at the previous time step, as all of the previous work has been done on the basis that the damper is instantaneous, this delay rate looks as making the damper react after a period of time to the velocity of the suspension movement, i.e. the difference between looking back one time step or 5 time steps. An example of this is that previously when the suspension translated from compression to rebound movement, the damping would adjust from compression to rebound instantaneously. Within this section, by increasing this damper delay rate, it results in the compression damping still operating for a small duration when the suspension velocity changes from compression to rebound before switching to the desired rebound damping and vice versa. However, suspension can hit a so called flat spot when changing direction and considering this damper delay is formulated based on simulation time and not on duration of the direction of velocity, if the flat spot is long enough within the simulation then it can cause a situation were no damping is supplied to the suspension for a short duration (approximately the duration of the delay rate) i.e. if the flat spot between changing from compression to rebound is 3ms and the damper delay rate is 3ms, then the damping on the rebound direction of travel would essentially have no damping for first 3ms of the travel as the equation would not see any velocities within this duration. It is essential to note that this flat spot is induced by the external forces, such as, the weight of the vehicle, brake pressure, road geometry, vehicle acceleration etc. rather than a characteristic of the damper. However, due to the nature of the proposed delay rate it is deemed necessary to have discussed this as it is unlikely to respond like conventional damper modelling, although, this this delay rate does exist to some extent within reality.

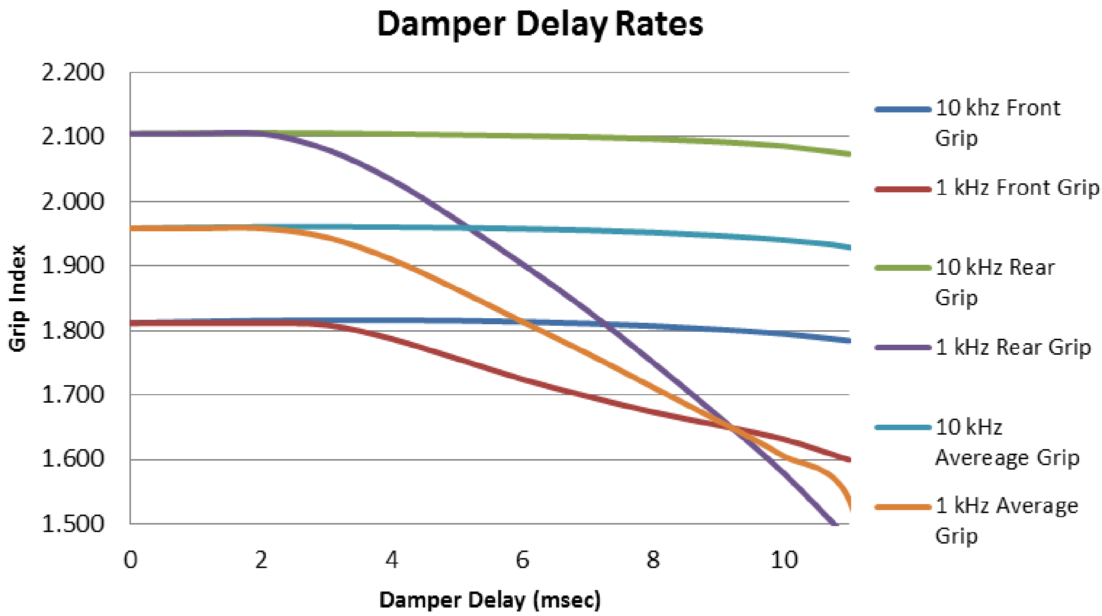

Figure 4-75 - Damper Delay Results

'Figure 4-75' shows the effects that increasing the damper delay rate has on the three main grip indexes, as you can see from the graph the optimum damper delay rate is at 3ms. 'Figure 4-75' shows that in order to get accurate results for this study a sample rate of 10,000Hz is required, otherwise the results after 3ms are dramatically inaccurate. The full table for the damper delay rates can be found in 'APPENDIX C – Damper Delay Rate Tables'.

The study will be developed to include both banking and braking into the vehicle model with the given optimum damper delay rate. This will be performed in the identical manor as the previous study in section '4.8.9 - 5 Degree of Freedom Banking and Braking', where the 'Average Grip Index' is optimised for each bank angle and then the results from 'Table 4-19' will be added to the optimised damping values at each bank angle to determine if the grip is still maintained.

4.9.1 Optimised Damping at Various Bank Angles

Table 4-20 - Optimised Damping at Various Bank Angles

Road Profile	Bank Angle	Damper Delay (milli Second)	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Random Road 2, Optimised Damping at Various Bank Angles											
Road 6	0	3	7.353	7.034	6.702	6.293	1.8169	2.110	4.840	4.989	1.964
Road 6	10	3	7.286	7.052	6.748	6.393	1.8189	2.113	4.840	4.989	1.966
Road 6	20	3	7.259	7.028	6.728	6.358	1.8251	2.119	4.836	4.988	1.972
Road 6	30	3	7.273	7.006	6.723	6.328	1.8355	2.129	4.831	4.988	1.982
Road 6	40	3	7.293	6.995	6.729	6.288	1.8494	2.143	4.822	4.987	1.996
Road 6	50	3	7.372	6.908	6.670	6.141	1.8664	2.159	4.809	4.986	2.013

'Table 4-20' shows the results produced by Microsoft Excels data solver tool, of the optimised damping values over road profile 6, to enable the maximum 'Average Grip Index' at different bank angles. These damping results can now be added to that of 'Table 4-19' at the different brake pressures to determine whether the original results from 'Table 4-19' play through to a different road profile and still maintain the high grip index to provide an increased grip index. It is interesting to note that 'Table 4-20' shows all grip indexes to improve as the vehicle banks more, interestingly enough this correlates to the fact that motorcycle tyres are softer at on the sides to improve edge grip. However, the way the vehicle has been modelled, this is not the case, the model represents banking by reducing the spring stiffness's, which allows the vehicle to sink into the corner when banking, equal to that of reality. Therefore, this also suggests that the spring stiffness's could be reduced and overall grip would be increased. However, due to the large braking pressure's which the given vehicle is subjected to, the spring stiffness's require to be stiffer to prevent the vehicle hitting the bump stops during heavy braking (8+ Bar).

From manipulating the model with 'Table 4-19 and Table 4-20's' results the following graphs were able to be produced.

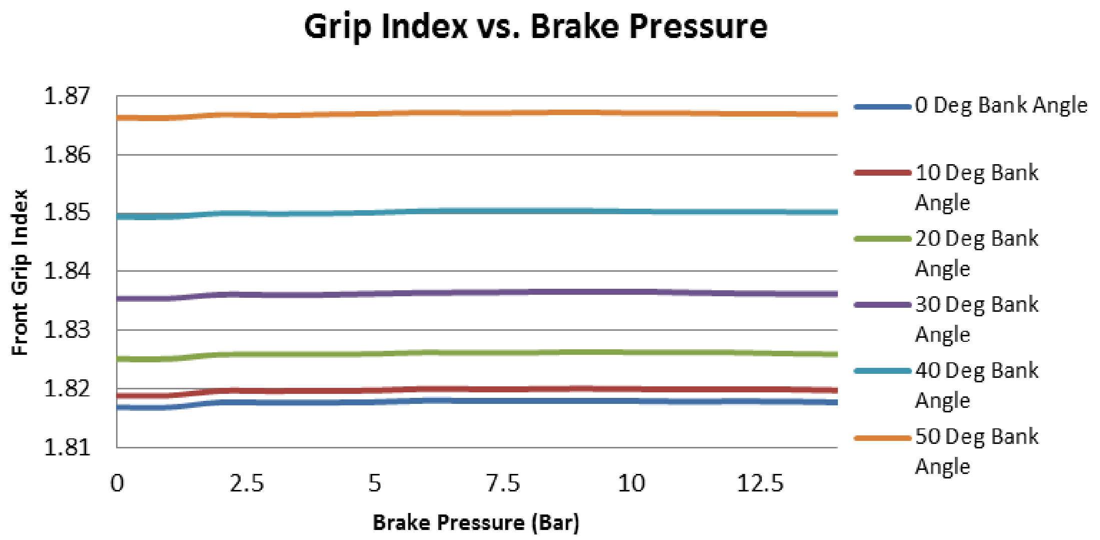

Figure 4-76 - Front Grip Index vs. Brake Pressure, with 3ms Delay

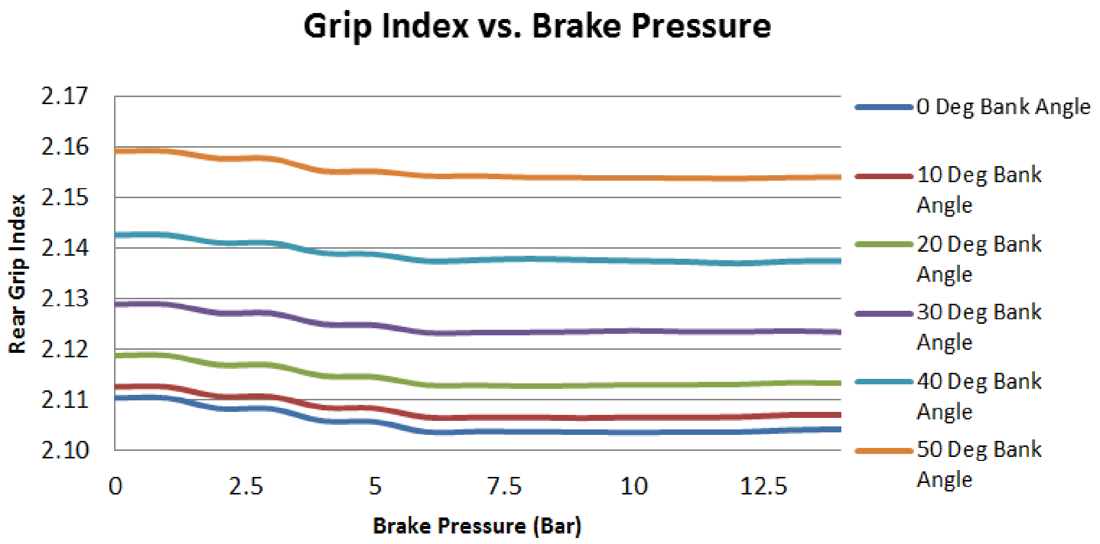

Figure 4-77 - Rear Grip Index vs. Brake Pressure, with 3ms Delay

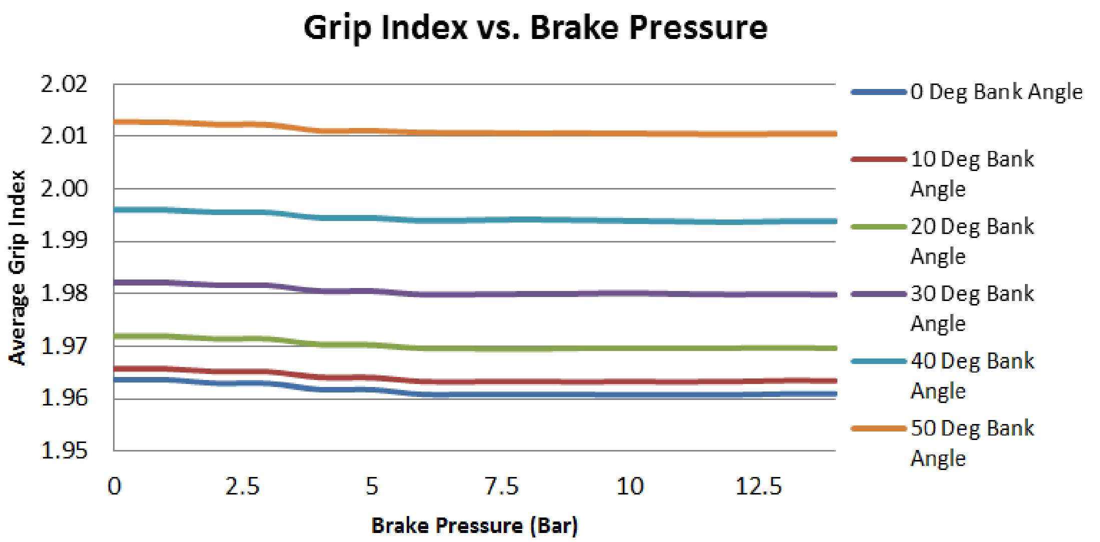

Figure 4-78 - Average Grip Index vs. Brake Pressure, with 3ms Delay

'Figure 4-76, Figure 4-77 and Figure 4-78' show the grip indexes of the vehicle model braking whilst banking at different bank angles. It can be seen from 'Figure 4-76, Figure 4-77 and Figure 4-78' that they follow the same pattern as 'Figure 4-72, Figure 4-73 and Figure 4-74'. Therefore, it can be stated the change in damping values for braking from 'Table 4-19', could be used as a lookup table for an active suspension unit for this vehicle. It can be seen from the results that the grip has been improved across the board by the 3ms damper delay as the 'Average Grip Index' is increased by approximately 0.25, an improvement of approximately 13.5% in grip at maximum bank angle. Each table of results which was used to create 'Figure 4-76, Figure 4-77 and Figure 4-78' can be found in 'APPENDIX D – Braking & Banking Results, with 3ms Damper Delay Rate'

It is clear that a motorcycle will bank and brake at different pressures and angles. Therefore, the suspension system could use a lookup table made up of the given values within 'Table 7-8, Table 7-9, Table 7-10, Table 7-11, Table 7-12 and Table 7-13' using live data from an accelerometer and brake pressure sensor fitted to the vehicle. 'Table 4-21' shows the optimised damping at various bank angles for various brake pressures; it shows a process in which the active suspension would adjust the damping. The adjustments could be made in a 'live' manor. Therefore, the suspension would be a reactive active suspension system which monitors the vehicle's bank angle and brake pressure in order to determine the correct damping values to use so that maximum grip can be obtained.

Table 4-21 - Optimised Damping at Various Bank Angles

Road Profile	Bank Angle	Damper Delay (milli Second)	Brake Pressure	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Random Road 2, Optimised Damping at Various Bank Angles												
Road 6	0	3	0	7.353	7.034	6.702	6.293	1.8169	2.110	4.840	4.989	1.964
Road 6	10	3	3	7.508	6.986	5.794	5.792	1.8196	2.111	4.835	4.988	1.965
Road 6	20	3	6	7.570	6.743	5.581	4.536	1.8262	2.113	4.826	4.988	1.970
Road 6	30	3	9	7.494	6.750	5.546	4.506	1.8366	2.123	4.820	4.987	1.980
Road 6	40	3	12	7.517	6.732	5.509	4.466	1.8503	2.137	4.811	4.987	1.994
Road 6	50	3	14	7.603	6.640	5.542	4.319	1.8669	2.154	4.798	4.986	2.010

Table 4-22 - Required Change in Damping due to Braking Pressure

Brake Pressure	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)
(Bar)	Change in	Change in	Change in	Change in
Required Change in Damping Due to Braking Pressure				
0				
1	0.000	0.000	0.000	0.000
2	0.222	-0.066	-0.954	-0.601
3	0.000	0.000	0.000	0.000
4	0.166	-0.270	0.529	-1.221
5	-0.196	0.088	-0.033	0.000
6	0.119	-0.037	-0.689	0.000
7	-0.055	0.013	-0.012	0.000
8	-0.016	0.002	-0.004	0.000
9	-0.020	0.015	-0.014	0.000
10	0.006	-0.003	-0.010	0.000
11	0.004	-0.011	-0.029	0.000
12	-0.007	0.008	-0.005	0.000
13	0.004	-0.003	0.097	0.000
14	0.004	-0.003	-0.005	0.000

Table 4-23 - Required Change in Damping Due to Bank Angle

Bank Angle	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)
(Degrees)	Change in	Change in	Change in	Change in
Required Change in Damping Due to Bank Angle				
0				
10	-0.067	0.018	0.047	0.100
20	-0.027	-0.024	-0.020	-0.035
30	0.015	-0.022	-0.005	-0.030
40	0.020	-0.011	0.006	-0.040
50	0.078	-0.086	-0.059	-0.147

The report has proved that in order to achieve maximum grip that damping has to be adjusted dependent on the scenario the vehicle is being subjected to. Therefore, the report generates 'Table 4-22 and Table 4-23' which state the required adjustment of damping to ensure that the grip level is maintained throughout the given scenarios. The report proves that the adjustments play 'across the board', i.e. the adjustments a damper with different delay rates. The report concludes that there is an optimum damper delay rate, which is given at 3ms. From 'Table 4-22 and Table 4-23' an active suspension system can be modelled to optimise the grip indexes in a corner entry scenario i.e. when the motorcycle brakes and banks into the corner. However, in order to adequately optimise rear grip a driving input should be implemented into the model. In order to ensure that the parametric nature of the model is continued the drive input should be done through RPM and gear. Parameters such as gear box specifications, final drive gearing, chain length, swinging arm length and swinging arm angle would be required in order to produce realistic pitching results at the rear sprung displacements.

5.0 DISSCUSSION

This section of the report outlines the difficulties face within the project.

There were several difficulties found when modelling the MATLAB/Simulink models, these were mainly due to the lack of experience and training available for using the software. The process of modelling the Simulink models was more of a 'learn as you go' type process. However, there was some support from my supervisors. The main issue which arose with using the Simulink modelling process was enabling the parametric compression and rebound damping, as each time this was introduced into the model, it resulted in using compression damping for longer than it should before switching over to rebound. Many weeks were spent on this issue and it resulted in an inefficient use of time, when this had already been completed and confirmed that this worked within the Microsoft Excel models. Therefore, it was at this point which the modelling process stopped with MATLAB/Simulink. This is not to say that MATLAB/Simulink is not capable of accomplishing this task, it is solely that in the time frame I could not find the solution even with the aid of multiple lecturers assistance. Also there was a difficulty faced when producing graphs, this was that the scope was used to present graphs, which did not provide legends, and axis definitions. Therefore, these manually had to be added to the thesis. With the current knowledge, the graphs would have been sent to 'workspace' rather than scope as this would have allowed for more post processing of the results. The modelling environment also proved difficult within MATLAB/Simulink for the damper delay rate, as for the same reasons in which the correct compression and rebound damping wouldn't work. Further time was spent on attempting to make the simulation use the value of the previous iteration (or specific time duration prior to the current), which resulted in the inability to complete the damper delay rate study within the MATLAB/Simulink modelling environment. Once again, it is felt that the software is more than capable of this, it is solely that the advice on how to achieve this was not available and that too much time was spent on the process of attempting to achieve this and therefore, abandoned, so that the study could still continue.

The experimental data was obtained was through working with the Be Wiser Kawasaki Super Stock Team. The suspension data was received from the Óhlins technician Andrew White, where we used calibrated measuring tools from his race truck workshop to determine the exact spring stiffness's which were fitted to the ZX-10R Kawasaki, we also used Óhlins data spec cards to attempt to identify the damping values which were in the bike. However, where the damper testing facility was at his head office and not available in the race truck, we could not test the specific damping that the bike was subjected to during the Knock Hill Race event. However, this was not overly necessary as the study was to identify the correct damping values for specific scenarios. In order to achieve the data logged data, it required the use of sponsorship for the team so that the 2D loggers could be purchased, which I played a part in obtaining. Once the sponsorship was obtained, the process of designing & manufacturing wiring looms for the team was required, which I completed in order to enable the success of the team having data logging for the entire season. Each sensor required calibration & zeroing prior to each session in which the vehicle was being used; this was done to ensure accuracy in the data being recorded. Then through contact with the 2D track support, assistance in using the software was obtained.

The main issue with the Microsoft Excel model which presented itself was the pitch equation of motion, as this used the vehicle inertia within the equation. However, when the traditional equation for vehicle inertia was used the results were in-accurate. Therefore, through multiple checks of the model formulation and studying of the Microsoft Excel calculations, different values for the inertia were implemented into the model to determine the correct response. It can be seen from 'Section 4.1 Vehicle Parameters' that the vehicle inertia is calculated from the sum of sprung and un-sprung masses. This is because it produced the most realistic results for the simulations. The other issue with using Microsoft Excel was the integration to simulate the damper delay rates, as the 10,000 Hz simulations took an average of 30 minutes when using the Microsoft Excel Data Solver Tool to identify the optimum grip index when adjusting the compression and rebound values as presented within 'Section 4.9 5 Degree of Freedom, Damper Delay Rates', this was extremely time consuming for little adjustments. The scale in which the damping within Microsoft Excel model was from 0.2 to 30 Ns/mm, as below 0.2Ns/mm the simulation would go unstable, although this was deemed an acceptable low limit, as no vehicle would be provided with this little damping as it would be extremely unstable in reality.

The bump stops within the model proved to take a while to simulate accurately, as initially this was done by implementing an additional high stiffness spring/damper equation. However, the spring/damper equation resulted in the vehicle bouncing rather dramatically off the stops. Therefore, after a lot of adjustment on the stiffness and damping values, it was found that the most realistic result was a soft spring with a large amount of damping in order to stop the suspension travel, yet not hold the suspension within this area of travel. Thus, allowing the suspension travel to literally hit the bump stop and stay there if an external force is still acting on it, and to leave the bump stop as soon as the external forces reduces. Also dynamic damping proved to be extremely difficult to model within Microsoft Excel, dynamic damping is referred to as progressive damping, due to the parametric nature in which the model was required to be in meant that extremely complex IF statements would have been needed to be created and extensive testing on the reliability of the IF statements would have been required. However, it is felt that the stages in which the scenarios were set, were staggered enough to render this non-essential for the current study.

6.0 CONCLUSION

The report has demonstrated the process involved with the creation of ¼ and full vehicle models within Microsoft Excel and Mathworks Matlab Simulink. It has focused on the modelling aspect of the project, discussing the results acquired throughout in order to develop the study.

- The results shown in section '4.8.3', on 'Table 4-6', state that there is a clear coloration between the step profile duration, the damping values between the front & rear and state the achievable grip gains. This table shows that there are specific ratios between the front and rear damping which can be used over a variety of step profiles to achieve maximum grip, and improve safety and handling.
- 'Table 4-22 and Table 4-23' determines a clear adjustment of damping in form of a pattern so that maximum grip can be maintained whilst braking and banking the vehicle at different angles and brake pressures.
- This research determines that for the given vehicle parameters that a damper delay rate of 3ms for front and rear damping can increase average tyre grip by an average of 13.5%.
- The project has shown how the objectives have been completed; from this report it is clear that the project has been successful and has identified relationships between damping and vehicle grip which have not previously been published or identified.
- 'Section 4.8 - 5 Degree of Freedom Grip Study' clearly shows how dramatically the grip can vary when the damping is not adjusted based on speed. It clearly demonstrates that in some instances that the wrong damping can provide good grip at lower speeds and high speeds. However, through the midrange of the speed increase, the grip dramatically reduces, further than that of the higher speeds, which could cause the instance of a crash, within the instance of a racing environment, for example, whilst traveling behind a safety car within a race, where the lap times are slower than the race lap times, similar to that of the midrange suggested speed.
- The thesis has provided an invaluable insight into the fundamental knowledge of creating an advanced active damping system which monitors vehicle motion and controls to determine the correct damping of the vehicle to maintain the maximum grip/contact with the road.

- The thesis provides additional information with regards to modelling suspension and variables such as bump stops and top out springs. The project has included the simulation of braking and used measured parameters of the vehicle; this provides valuable insight into the effects which braking can have on the system and enables the development of the vehicle away from the motorcycle itself. Thus, remote simulation development of the vehicle would reduce physical testing time. Due to the parametric nature of the model produced within the project, the model can be used for alternative studies, such as the manipulation of spring stiffness's to optimise the grip indexes.

7.0 RECCOMENDATIONS FOR FUTURE WORK

Evidence of the report suggest, that the 5 Degree of Freedom model could benefit from the implementation of 'drive' within the system, to enable a similar study into the relationship between 'drive', 'grip' and damping values. However, the report states in section '4.9.1' the parameter requirements of implementing 'drive' within the system and with a lack of information about the vehicle's engine parameters, creating an 'accurate' model would require a lot of trial and error. Thus, the focus of the project was kept on the 'braking case' scenario and 'banking' scenarios. Therefore, the project was completed to the highest standard as the main model formulation functions correctly, as proven in section '4.7.2' and the project has produced relevant data regarding the development of active suspension systems. Although, for future developments this would be a must to fully analyse the system, also traction control could then be implemented to see the advantages and disadvantages to the grip of using traction control within the racing environment.

The current project was limited by the fact there is not a rider within the model. The rider can have a tremendous influence on the handling of the vehicle, this is because some riders prefer a different setup which is capable of making them more comfortable and can prevent grip, the other factor is that the rider can offset the centre of gravity whilst riding and also is never that consistent, this is shown in 'Figure 4-39' where the braking is very erratic. However, it can be stated that the given 5 Degree of Freedom model produced from this project can be used to develop the vehicle and any development of the vehicle will only benefit the rider, and so long as the rider rides correctly, the simulated developments will develop the vehicle in real life application. The model could be developed to include this rider to look into corner case scenarios where the lean angle of the rider affects the travel of the suspension.

If the current project was to be extended it is recommended that the implementation of 'drive' were to be modelled to analyse the effects of grip within different scenarios and to create more data tables for a further developed of an active damping system. It would also be recommended that a full motorcycle model were to be created in a multi-body systems package capable of running a damper algorithm to optimise grip based on live data of the model, to simulate a realistic active damping system. Once the multi-body system model has been created the analysis of yaw side slip during braking, cornering and accelerating could be analysed to further develop either an algorithm or more lookup tables to further develop an advanced active damping suspension system.

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APPENDIX A – Random Road Profile’s

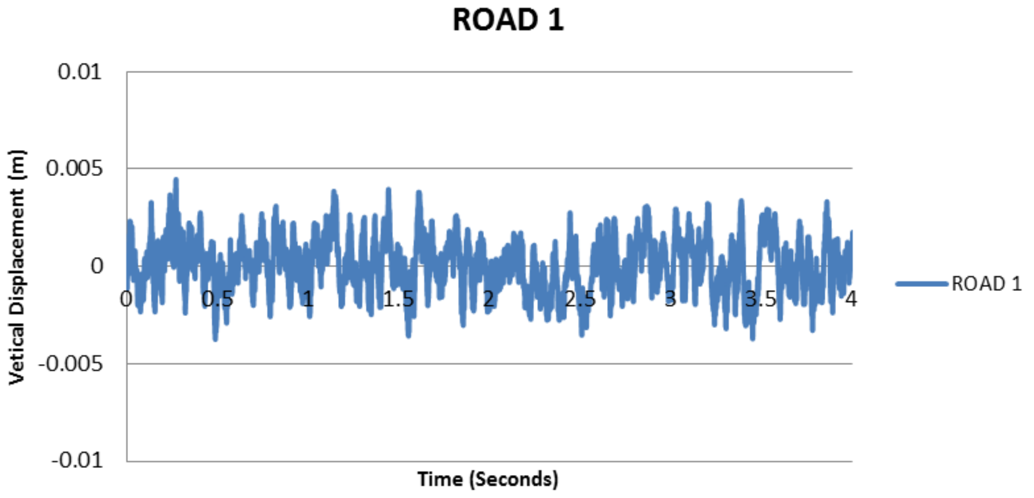


Figure 7-1 - Random Road Profile 1

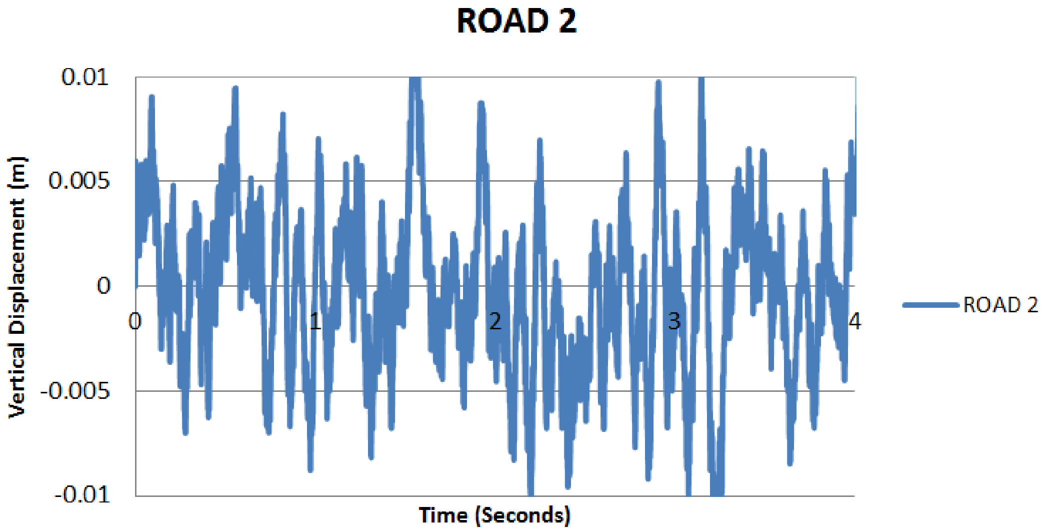


Figure 7-2 - Random Road Profile 2

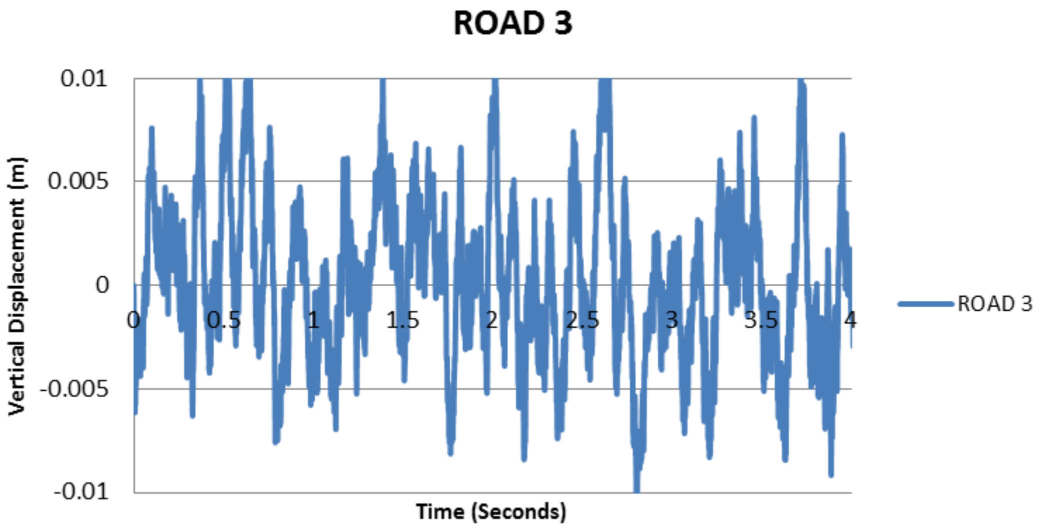


Figure 7-3 - Random Road Profile 3

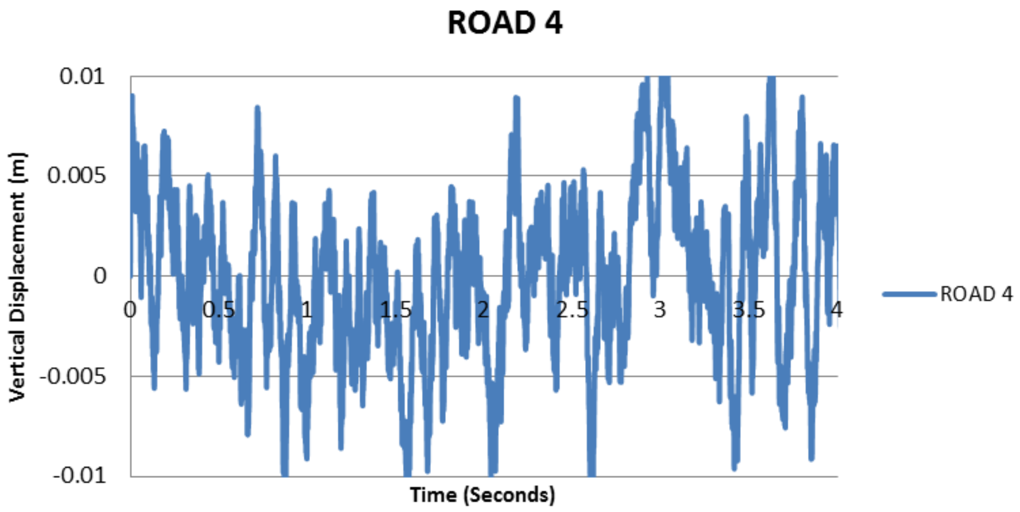


Figure 7-4 - Random Road 4

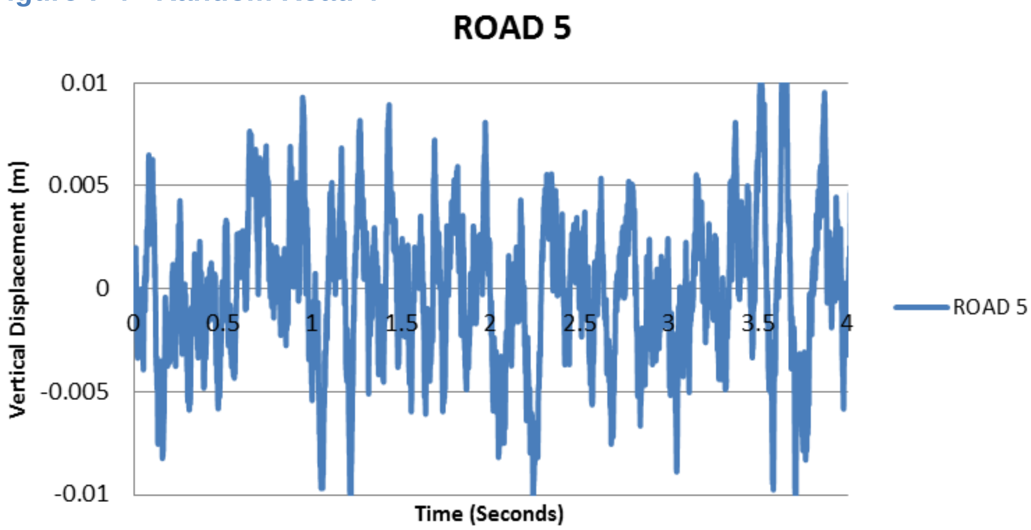


Figure 7-5 - Random Road 5

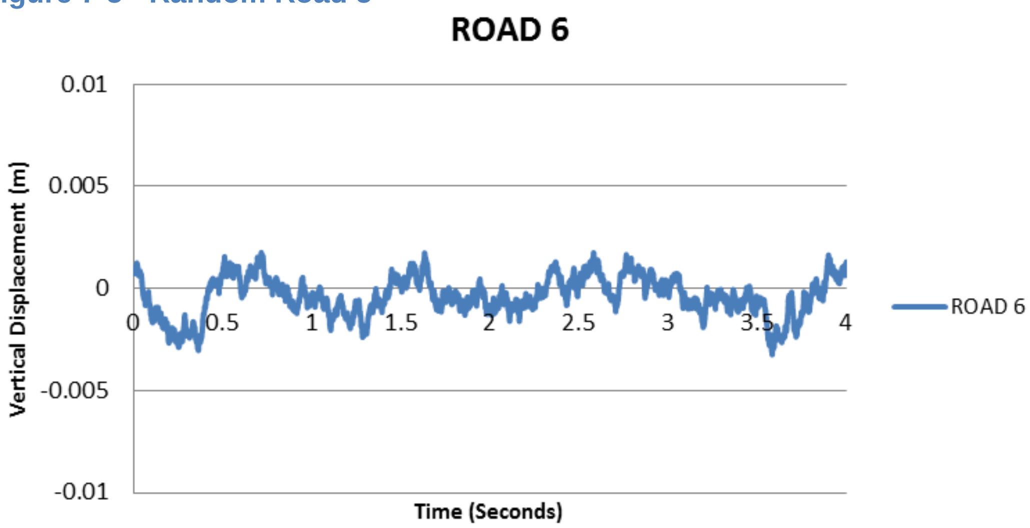


Figure 7-6 - Random Road 6

APPENDIX B – Braking & Banking Results

Table 7-1 - Braking Results at 0 Degrees of Banking

Road Profile	Bank Angle	Brake Pressure	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Random Road 2, 0 Degrees of Bank Angle											
Road 2	0	0	6.834	6.397	5.334	4.926	1.4399	1.784	4.910	4.996	1.612
Road 2	0	1	6.834	6.397	5.334	4.926	1.4399	1.784	4.910	4.996	1.612
Road 2	0	2	7.056	6.331	4.380	4.325	1.4412	1.774	4.908	4.996	1.608
Road 2	0	3	7.056	6.331	4.380	4.325	1.4411	1.774	4.908	4.996	1.608
Road 2	0	4	7.223	6.062	4.909	3.104	1.4409	1.753	4.905	4.996	1.597
Road 2	0	5	7.027	6.149	4.875	3.104	1.4407	1.752	4.905	4.996	1.597
Road 2	0	6	7.146	6.112	4.187	3.104	1.4411	1.744	4.904	4.996	1.592
Road 2	0	7	7.091	6.125	4.175	3.104	1.4409	1.743	4.904	4.996	1.592
Road 2	0	8	7.075	6.127	4.171	3.104	1.4410	1.743	4.904	4.996	1.592
Road 2	0	9	7.055	6.141	4.157	3.104	1.4410	1.743	4.904	4.996	1.592
Road 2	0	10	7.061	6.138	4.148	3.104	1.4410	1.743	4.904	4.996	1.592
Road 2	0	11	7.065	6.126	4.119	3.104	1.4411	1.741	4.904	4.996	1.591
Road 2	0	12	7.058	6.134	4.114	3.104	1.4412	1.741	4.904	4.996	1.591
Road 2	0	13	7.062	6.131	4.211	3.104	1.4412	1.743	4.904	4.996	1.592
Road 2	0	14	7.066	6.129	4.206	3.104	1.4412	1.743	4.904	4.996	1.592

Table 7-2 - Braking Results at 10 Degrees of Banking

Road Profile	Bank Angle	Brake Pressure	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Random Road 2, 10 Degrees of Bank Angle											
Road 2	10	0	6.813	6.381	5.306	4.940	1.4450	1.790	4.910	4.996	1.618
Road 2	10	1	6.813	6.381	5.306	4.940	1.4450	1.790	4.910	4.996	1.618
Road 2	10	2	7.035	6.315	4.352	4.339	1.4463	1.780	4.907	4.996	1.613
Road 2	10	3	7.035	6.315	4.352	4.339	1.4462	1.780	4.907	4.996	1.613
Road 2	10	4	7.201	6.046	4.881	3.118	1.4460	1.759	4.905	4.996	1.603
Road 2	10	5	7.005	6.133	4.847	3.118	1.4458	1.759	4.904	4.996	1.603
Road 2	10	6	7.124	6.096	4.158	3.118	1.4462	1.750	4.903	4.996	1.598
Road 2	10	7	7.069	6.109	4.147	3.118	1.4461	1.750	4.903	4.996	1.598
Road 2	10	8	7.053	6.110	4.143	3.118	1.4462	1.750	4.903	4.996	1.598
Road 2	10	9	7.033	6.125	4.129	3.118	1.4461	1.749	4.903	4.996	1.598
Road 2	10	10	7.040	6.122	4.120	3.118	1.4462	1.749	4.903	4.996	1.598
Road 2	10	11	7.043	6.110	4.091	3.118	1.4462	1.748	4.903	4.996	1.597
Road 2	10	12	7.037	6.118	4.086	3.118	1.4463	1.748	4.903	4.996	1.597
Road 2	10	13	7.040	6.115	4.183	3.118	1.4462	1.750	4.903	4.996	1.598
Road 2	10	14	7.044	6.113	4.178	3.118	1.4463	1.750	4.903	4.996	1.598

Table 7-3 - Braking Results at 20 Degrees of Banking

Road Profile	Bank Angle	Brake Pressure	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Random Road 2, 20 Degrees of Bank Angle											
Road 2	20	0	6.766	6.374	5.300	4.831	1.4606	1.809	4.908	4.996	1.635
Road 2	20	1	6.766	6.374	5.300	4.831	1.4606	1.808	4.908	4.996	1.635
Road 2	20	2	6.988	6.309	4.346	4.230	1.4618	1.798	4.905	4.996	1.630
Road 2	20	3	6.988	6.309	4.346	4.230	1.4618	1.798	4.905	4.996	1.630
Road 2	20	4	7.154	6.039	4.875	3.009	1.4617	1.775	4.903	4.996	1.618
Road 2	20	5	6.959	6.127	4.841	3.009	1.4615	1.775	4.903	4.996	1.618
Road 2	20	6	7.078	6.090	4.152	3.009	1.4618	1.766	4.902	4.996	1.614
Road 2	20	7	7.022	6.102	4.141	3.009	1.4617	1.766	4.902	4.996	1.614
Road 2	20	8	7.007	6.104	4.137	3.009	1.4617	1.766	4.902	4.996	1.614
Road 2	20	9	6.987	6.119	4.123	3.009	1.4617	1.765	4.902	4.996	1.613
Road 2	20	10	6.993	6.115	4.114	3.009	1.4618	1.765	4.902	4.996	1.613
Road 2	20	11	6.997	6.104	4.085	3.009	1.4619	1.764	4.901	4.996	1.613
Road 2	20	12	6.990	6.112	4.080	3.009	1.4619	1.764	4.901	4.996	1.613
Road 2	20	13	6.994	6.109	4.177	3.009	1.4619	1.765	4.902	4.996	1.614
Road 2	20	14	6.998	6.106	4.172	3.009	1.4616	1.765	4.902	4.996	1.614

Table 7-4 - Braking Results at 30 Degrees of Banking

Road Profile	Bank Angle	Brake Pressure	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Random Road 2, 30 Degrees of Bank Angle											
Road 2	30	0	6.699	6.349	5.183	4.836	1.4865	1.839	4.906	4.996	1.663
Road 2	30	1	6.699	6.349	5.183	4.836	1.4866	1.839	4.906	4.996	1.663
Road 2	30	2	6.921	6.283	4.229	4.235	1.4878	1.829	4.903	4.996	1.658
Road 2	30	3	6.921	6.283	4.229	4.235	1.4878	1.829	4.903	4.996	1.658
Road 2	30	4	7.088	6.014	4.758	3.014	1.4877	1.807	4.901	4.996	1.647
Road 2	30	5	6.892	6.101	4.725	3.014	1.4878	1.806	4.900	4.996	1.647
Road 2	30	6	7.011	6.064	4.036	3.014	1.4880	1.797	4.899	4.996	1.643
Road 2	30	7	6.956	6.077	4.024	3.014	1.4878	1.797	4.899	4.996	1.642
Road 2	30	8	6.940	6.079	4.020	3.014	1.4877	1.796	4.899	4.996	1.642
Road 2	30	9	6.920	6.093	4.007	3.014	1.4877	1.796	4.899	4.996	1.642
Road 2	30	10	6.926	6.090	3.997	3.014	1.4878	1.796	4.899	4.996	1.642
Road 2	30	11	6.930	6.078	3.968	3.014	1.4877	1.795	4.899	4.996	1.641
Road 2	30	12	6.923	6.086	3.963	3.014	1.4877	1.795	4.899	4.996	1.641
Road 2	30	13	6.927	6.083	4.060	3.014	1.4876	1.797	4.899	4.996	1.642
Road 2	30	14	6.931	6.081	4.055	3.014	1.4876	1.796	4.899	4.996	1.642

Table 7-5 - Braking Results at 40 Degrees of Banking

Road Profile	Bank Angle	Brake Pressure	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Random Road 2, 40 Degrees of Bank Angle											
Road 2	40	0	6.619	6.331	5.054	4.829	1.5232	1.882	4.902	4.996	1.703
Road 2	40	1	6.619	6.331	5.054	4.829	1.5232	1.882	4.902	4.996	1.703
Road 2	40	2	6.841	6.266	4.100	4.228	1.5245	1.872	4.899	4.996	1.698
Road 2	40	3	6.841	6.266	4.100	4.228	1.5245	1.872	4.899	4.996	1.698
Road 2	40	4	7.007	5.996	4.629	3.007	1.5245	1.850	4.897	4.996	1.687
Road 2	40	5	6.811	6.083	4.595	3.007	1.5244	1.849	4.896	4.996	1.687
Road 2	40	6	6.930	6.046	3.906	3.007	1.5246	1.839	4.895	4.996	1.682
Road 2	40	7	6.875	6.059	3.895	3.007	1.5246	1.839	4.895	4.996	1.682
Road 2	40	8	6.859	6.061	3.891	3.007	1.5243	1.839	4.895	4.996	1.682
Road 2	40	9	6.839	6.075	3.877	3.007	1.5243	1.839	4.895	4.996	1.682
Road 2	40	10	6.846	6.072	3.868	3.007	1.5243	1.839	4.895	4.996	1.682
Road 2	40	11	6.849	6.061	3.839	3.007	1.5242	1.838	4.895	4.996	1.681
Road 2	40	12	6.843	6.069	3.834	3.007	1.5243	1.838	4.895	4.996	1.681
Road 2	40	13	6.847	6.066	3.931	3.007	1.5245	1.840	4.895	4.996	1.682
Road 2	40	14	6.850	6.063	3.926	3.007	1.5247	1.840	4.895	4.996	1.682

Table 7-6 - Braking Results at 50 Degrees of Banking

Road Profile	Bank Angle	Brake Pressure	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Random Road 2, 50 Degrees of Bank Angle											
Road 2	50	0	6.572	6.333	4.975	4.820	1.5705	1.938	4.896	4.996	1.754
Road 2	50	1	6.572	6.333	4.975	4.820	1.5705	1.938	4.896	4.996	1.754
Road 2	50	2	6.794	6.267	4.021	4.219	1.5715	1.928	4.893	4.996	1.750
Road 2	50	3	6.794	6.267	4.021	4.219	1.5716	1.928	4.893	4.996	1.750
Road 2	50	4	6.960	5.998	4.550	2.998	1.5712	1.906	4.891	4.996	1.738
Road 2	50	5	6.764	6.085	4.516	2.998	1.5716	1.905	4.891	4.996	1.738
Road 2	50	6	6.883	6.048	3.827	2.998	1.5717	1.895	4.889	4.996	1.734
Road 2	50	7	6.828	6.061	3.816	2.998	1.5716	1.896	4.889	4.996	1.734
Road 2	50	8	6.812	6.063	3.812	2.998	1.5715	1.896	4.889	4.995	1.734
Road 2	50	9	6.792	6.077	3.798	2.998	1.5716	1.896	4.889	4.995	1.734
Road 2	50	10	6.799	6.074	3.789	2.998	1.5718	1.895	4.889	4.995	1.733
Road 2	50	11	6.802	6.062	3.760	2.998	1.5716	1.894	4.889	4.995	1.733
Road 2	50	12	6.796	6.070	3.755	2.998	1.5718	1.894	4.889	4.995	1.733
Road 2	50	13	6.800	6.067	3.852	2.998	1.5717	1.896	4.889	4.996	1.734
Road 2	50	14	6.803	6.065	3.847	2.998	1.5718	1.896	4.889	4.996	1.734

APPENDIX C – Damper Delay Rate Tables

Table 7-7 - Damper Delay Rate Results

Road Profile	Bank Angle	Brake Pressure (Bar)	Damper Delay (milli Second)	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Random Road 6, Optimised Average Grip For Damper Delay Rates 10,000Hz												
Road 6	0	0	0	6.8343642	6.397	5.334	4.926	1.812	2.1050	4.800	4.988	1.958
Road 6	0	0	1	6.834	6.397	5.334	4.926	1.8137	2.106	4.807	4.988	1.960
Road 6	0	0	2	6.834	6.397	5.334	4.926	1.8155	2.107	4.816	4.988	1.961
Road 6	0	0	3	6.834	6.397	5.334	4.926	1.8163	2.106	4.824	4.988	1.961
Road 6	0	0	4	6.834	6.397	5.334	4.926	1.8162	2.105	4.833	4.988	1.960
Road 6	0	0	5	6.834	6.397	5.334	4.926	1.8153	2.103	4.842	4.988	1.959
Road 6	0	0	6	6.834	6.397	5.334	4.926	1.8135	2.102	4.851	4.989	1.958
Road 6	0	0	7	6.834	6.397	5.334	4.926	1.8109	2.100	4.861	4.989	1.955
Road 6	0	0	8	6.834	6.397	5.334	4.926	1.8070	2.097	4.871	4.989	1.952
Road 6	0	0	9	6.834	6.397	5.334	4.926	1.8018	2.092	4.881	4.989	1.947
Road 6	0	0	10	6.834	6.397	5.334	4.926	1.7948	2.086	4.892	4.989	1.940
Road 6	0	0	11	6.834	6.397	5.334	4.926	1.7842	2.073	4.903	4.989	1.929
Road 6	0	0	12	6.8343642	6.397	5.334	4.926	1.759	2.0429	4.917	4.989	1.901

Road Profile	Bank Angle	Brake Pressure (Bar)	Damper Delay (milli Second)	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Random Road 6, Optimised Average Grip For Damper Delay Rates 1,000Hz												
Road 6	0	0	0	6.8343642	6.397	5.334	4.926	1.812	2.105	4.800	4.988	1.958
Road 6	0	0	1	6.834	6.397	5.334	4.926	1.812	2.105	4.800	4.988	1.958
Road 6	0	0	2	6.834	6.397	5.334	4.926	1.812	2.105	4.800	4.988	1.958
Road 6	0	0	3	6.834	6.397	5.334	4.926	1.809	2.081	4.830	4.988	1.945
Road 6	0	0	4	6.834	6.397	5.334	4.926	1.787	2.033	4.859	4.989	1.910
Road 6	0	0	5	6.834	6.397	5.334	4.926	1.756	1.971	4.889	4.989	1.864
Road 6	0	0	6	6.834	6.397	5.334	4.926	1.725	1.903	4.919	4.990	1.814
Road 6	0	0	7	6.834	6.397	5.334	4.926	1.698	1.831	4.949	4.990	1.764
Road 6	0	0	8	6.834	6.397	5.334	4.926	1.674	1.751	4.979	4.991	1.712
Road 6	0	0	9	6.834	6.397	5.334	4.926	1.653	1.667	5.008	4.991	1.660
Road 6	0	0	10	6.834	6.397	5.334	4.926	1.632	1.579	5.037	4.992	1.605
Road 6	0	0	11	6.834	6.397	5.334	4.926	1.600	1.476	5.065	4.993	1.538
Road 6	0	0	12	6.8343642	6.397	5.334	4.926	1.311	0.910	5.171	4.995	1.110

APPENDIX D – Braking & Banking Results, with 3ms Damper Delay Rate

Table 7-8 - Braking Results at 0 Degrees of Banking with 3ms Damper Delay Rate

Road Profile	Bank Angle	Damper Delay Rate (ms)	Brake Pressure	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Random Road 2, 0 Degrees of Bank Angle												
Road 6	0	3	0	7.353	7.034	6.702	6.293	1.8169	2.110	4.840	4.989	1.964
Road 6	0	3	1	7.353	7.034	6.702	6.293	1.8168	2.110	4.840	4.989	1.964
Road 6	0	3	2	7.575	6.968	5.748	5.692	1.8177	2.108	4.836	4.988	1.963
Road 6	0	3	3	7.575	6.968	5.748	5.692	1.8176	2.108	4.836	4.988	1.963
Road 6	0	3	4	7.742	6.698	6.276	4.471	1.8177	2.106	4.833	4.988	1.962
Road 6	0	3	5	7.546	6.786	6.243	4.471	1.8178	2.106	4.832	4.988	1.962
Road 6	0	3	6	7.665	6.749	5.554	4.471	1.8180	2.104	4.830	4.988	1.961
Road 6	0	3	7	7.610	6.761	5.543	4.471	1.8180	2.104	4.830	4.988	1.961
Road 6	0	3	8	7.594	6.763	5.539	4.471	1.8179	2.104	4.830	4.988	1.961
Road 6	0	3	9	7.574	6.778	5.525	4.471	1.8180	2.104	4.830	4.988	1.961
Road 6	0	3	10	7.580	6.774	5.515	4.471	1.8180	2.104	4.829	4.988	1.961
Road 6	0	3	11	7.584	6.763	5.487	4.471	1.8178	2.104	4.829	4.988	1.961
Road 6	0	3	12	7.577	6.771	5.481	4.471	1.8179	2.104	4.829	4.988	1.961
Road 6	0	3	13	7.581	6.768	5.578	4.471	1.8179	2.104	4.830	4.988	1.961
Road 6	0	3	14	7.585	6.766	5.574	4.471	1.8177	2.104	4.830	4.988	1.961

Table 7-9 - Braking Results at 10 Degrees of Banking with 3ms Damper Delay Rate

Road Profile	Bank Angle	Damper Delay Rate (ms)	Brake Pressure	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Random Road 2, 10 Degrees of Bank Angle												
Road 6	10	3	0	7.286	7.052	6.748	6.393	1.8189	2.113	4.840	4.989	1.966
Road 6	10	3	1	7.286	7.052	6.748	6.393	1.8189	2.113	4.840	4.989	1.966
Road 6	10	3	2	7.508	6.986	5.794	5.792	1.8197	2.111	4.835	4.988	1.965
Road 6	10	3	3	7.508	6.986	5.794	5.792	1.8196	2.111	4.835	4.988	1.965
Road 6	10	3	4	7.674	6.716	6.323	4.571	1.8197	2.108	4.832	4.988	1.964
Road 6	10	3	5	7.479	6.804	6.290	4.571	1.8197	2.108	4.831	4.988	1.964
Road 6	10	3	6	7.598	6.767	5.601	4.571	1.8200	2.107	4.829	4.988	1.963
Road 6	10	3	7	7.542	6.779	5.589	4.571	1.8199	2.107	4.829	4.988	1.963
Road 6	10	3	8	7.527	6.781	5.585	4.571	1.8200	2.107	4.829	4.988	1.963
Road 6	10	3	9	7.507	6.796	5.572	4.571	1.8200	2.106	4.829	4.988	1.963
Road 6	10	3	10	7.513	6.792	5.562	4.571	1.8200	2.107	4.829	4.988	1.963
Road 6	10	3	11	7.517	6.781	5.533	4.571	1.8199	2.107	4.829	4.988	1.963
Road 6	10	3	12	7.510	6.789	5.528	4.571	1.8200	2.107	4.829	4.988	1.963
Road 6	10	3	13	7.514	6.786	5.625	4.571	1.8199	2.107	4.829	4.988	1.963
Road 6	10	3	14	7.518	6.784	5.620	4.571	1.8198	2.107	4.829	4.988	1.963

Table 7-10 - Braking Results at 20 Degrees of Banking with 3ms Damper Delay Rate

Road Profile	Bank Angle	Damper Delay Rate (ms)	Brake Pressure	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Random Road 2, 20 Degrees of Bank Angle												
Road 6	20	3	0	7.259	7.028	6.728	6.358	1.8251	2.119	4.836	4.988	1.972
Road 6	20	3	1	7.259	7.028	6.728	6.358	1.8251	2.119	4.836	4.988	1.972
Road 6	20	3	2	7.481	6.962	5.774	5.757	1.8259	2.117	4.832	4.988	1.971
Road 6	20	3	3	7.481	6.962	5.774	5.757	1.8259	2.117	4.832	4.988	1.971
Road 6	20	3	4	7.647	6.693	6.303	4.536	1.8260	2.115	4.829	4.988	1.970
Road 6	20	3	5	7.451	6.780	6.269	4.536	1.8260	2.115	4.828	4.988	1.970
Road 6	20	3	6	7.570	6.743	5.581	4.536	1.8262	2.113	4.826	4.988	1.970
Road 6	20	3	7	7.515	6.756	5.569	4.536	1.8261	2.113	4.825	4.988	1.970
Road 6	20	3	8	7.499	6.758	5.565	4.536	1.8262	2.113	4.825	4.988	1.969
Road 6	20	3	9	7.479	6.772	5.551	4.536	1.8263	2.113	4.825	4.988	1.970
Road 6	20	3	10	7.486	6.769	5.542	4.536	1.8263	2.113	4.825	4.988	1.970
Road 6	20	3	11	7.489	6.757	5.513	4.536	1.8262	2.113	4.825	4.988	1.970
Road 6	20	3	12	7.483	6.765	5.508	4.536	1.8262	2.113	4.825	4.988	1.970
Road 6	20	3	13	7.486	6.763	5.605	4.536	1.8260	2.113	4.826	4.988	1.970
Road 6	20	3	14	7.490	6.760	5.600	4.536	1.8259	2.113	4.826	4.988	1.970

Table 7-11 - Braking Results at 30 Degrees of Banking with 3ms Damper Delay Rate

Road Profile	Bank Angle	Damper Delay Rate (ms)	Brake Pressure	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Random Road 2, 30 Degrees of Bank Angle												
Road 6	30	3	0	7.273	7.006	6.723	6.328	1.8355	2.129	4.831	4.988	1.982
Road 6	30	3	1	7.273	7.006	6.723	6.328	1.8354	2.129	4.831	4.988	1.982
Road 6	30	3	2	7.496	6.940	5.769	5.727	1.8361	2.127	4.826	4.988	1.982
Road 6	30	3	3	7.496	6.940	5.769	5.727	1.8361	2.127	4.826	4.988	1.982
Road 6	30	3	4	7.662	6.670	6.298	4.506	1.8361	2.125	4.823	4.988	1.981
Road 6	30	3	5	7.466	6.758	6.264	4.506	1.8363	2.125	4.822	4.987	1.981
Road 6	30	3	6	7.585	6.721	5.575	4.506	1.8364	2.123	4.820	4.987	1.980
Road 6	30	3	7	7.530	6.733	5.564	4.506	1.8365	2.123	4.820	4.987	1.980
Road 6	30	3	8	7.514	6.735	5.560	4.506	1.8366	2.123	4.820	4.987	1.980
Road 6	30	3	9	7.494	6.750	5.546	4.506	1.8366	2.123	4.820	4.987	1.980
Road 6	30	3	10	7.500	6.746	5.537	4.506	1.8366	2.124	4.820	4.987	1.980
Road 6	30	3	11	7.504	6.735	5.508	4.506	1.8365	2.123	4.820	4.987	1.980
Road 6	30	3	12	7.497	6.743	5.503	4.506	1.8363	2.123	4.820	4.987	1.980
Road 6	30	3	13	7.501	6.740	5.600	4.506	1.8363	2.124	4.820	4.988	1.980
Road 6	30	3	14	7.505	6.738	5.595	4.506	1.8363	2.123	4.820	4.988	1.980

Table 7-12 - Braking Results at 40 Degrees of Banking with 3ms Damper Delay Rate

Road Profile	Bank Angle	Damper Delay Rate (ms)	Brake Pressure	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Random Road 2, 40 Degrees of Bank Angle												
Road 6	40	3	0	7.293	6.995	6.729	6.288	1.8494	2.143	4.822	4.987	1.996
Road 6	40	3	1	7.293	6.995	6.729	6.288	1.8494	2.143	4.822	4.987	1.996
Road 6	40	3	2	7.515	6.929	5.775	5.687	1.8500	2.141	4.818	4.987	1.996
Road 6	40	3	3	7.515	6.929	5.775	5.687	1.8499	2.141	4.818	4.987	1.995
Road 6	40	3	4	7.682	6.660	6.304	4.466	1.8500	2.139	4.814	4.987	1.994
Road 6	40	3	5	7.486	6.747	6.270	4.466	1.8501	2.139	4.813	4.987	1.994
Road 6	40	3	6	7.605	6.710	5.582	4.466	1.8504	2.137	4.811	4.987	1.994
Road 6	40	3	7	7.550	6.723	5.570	4.466	1.8504	2.138	4.811	4.987	1.994
Road 6	40	3	8	7.534	6.725	5.566	4.466	1.8505	2.138	4.811	4.987	1.994
Road 6	40	3	9	7.514	6.739	5.552	4.466	1.8505	2.138	4.811	4.987	1.994
Road 6	40	3	10	7.520	6.736	5.543	4.466	1.8503	2.137	4.811	4.987	1.994
Road 6	40	3	11	7.524	6.724	5.514	4.466	1.8503	2.137	4.811	4.987	1.994
Road 6	40	3	12	7.517	6.732	5.509	4.466	1.8503	2.137	4.811	4.987	1.994
Road 6	40	3	13	7.521	6.729	5.606	4.466	1.8502	2.137	4.811	4.987	1.994
Road 6	40	3	14	7.525	6.727	5.601	4.466	1.8502	2.137	4.811	4.987	1.994

Table 7-13 - Braking Results at 50 Degrees of Banking with 3ms Damper Delay Rate

Road Profile	Bank Angle	Damper Delay Rate (ms)	Brake Pressure	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Random Road 2, 50 Degrees of Bank Angle												
Road 6	50	3	0	7.372	6.908	6.670	6.141	1.8664	2.159	4.809	4.986	2.013
Road 6	50	3	1	7.372	6.908	6.670	6.141	1.8663	2.159	4.809	4.986	2.013
Road 6	50	3	2	7.594	6.843	5.716	5.540	1.8669	2.158	4.804	4.986	2.012
Road 6	50	3	3	7.594	6.843	5.716	5.540	1.8667	2.158	4.804	4.986	2.012
Road 6	50	3	4	7.760	6.573	6.245	4.319	1.8669	2.155	4.801	4.986	2.011
Road 6	50	3	5	7.564	6.661	6.211	4.319	1.8670	2.155	4.800	4.986	2.011
Road 6	50	3	6	7.684	6.624	5.522	4.319	1.8672	2.154	4.798	4.986	2.011
Road 6	50	3	7	7.628	6.636	5.511	4.319	1.8671	2.154	4.798	4.986	2.011
Road 6	50	3	8	7.612	6.638	5.507	4.319	1.8672	2.154	4.798	4.986	2.011
Road 6	50	3	9	7.592	6.653	5.493	4.319	1.8673	2.154	4.797	4.986	2.011
Road 6	50	3	10	7.599	6.649	5.484	4.319	1.8671	2.154	4.797	4.986	2.011
Road 6	50	3	11	7.602	6.638	5.455	4.319	1.8671	2.154	4.797	4.986	2.010
Road 6	50	3	12	7.596	6.646	5.450	4.319	1.8670	2.154	4.797	4.986	2.010
Road 6	50	3	13	7.600	6.643	5.547	4.319	1.8670	2.154	4.798	4.986	2.010
Road 6	50	3	14	7.603	6.640	5.542	4.319	1.8669	2.154	4.798	4.986	2.010

APPENDIX E – Viva Presentation Slides

The 5th Degree of Freedom

Coventry University

- $$m_{fu} * \ddot{Z}_{fu} = \begin{pmatrix} \{K_{fu} * (U_f - Z_{fu}) * \cos\varphi\} + \{C_{fu} * (\dot{U}_f - \dot{Z}_{fu})\} + \\ + \left\{K_{fseff} * \left((Z_{fs} + \theta * a) - Z_{fu}\right) * \cos\varphi\right\} + \left\{C_{fs} * \left((\dot{Z}_{fs} + \dot{\theta} * a) - \dot{Z}_{fu}\right)\right\} - \{m_{fu} * g\} \end{pmatrix} * \mu_{ground}$$
- $$m_{ru} * \ddot{Z}_{ru} = \\ (\{K_{ru} * (U_r - Z_{ru}) * \cos\varphi\} + \{C_{ru} * (\dot{U}_r - \dot{Z}_{ru})\} + \\ \left\{K_{rs} * \left((Z_{rs} - \theta * b) - Z_{ru}\right) * \cos\varphi\right\} + \left\{C_{rs} * \left((\dot{Z}_{rs} - \dot{\theta} * b) - \dot{Z}_{ru}\right)\right\} - \{m_{ru} * g\}\right) * \mu_{ground}$$
- $$m_{fs} * \ddot{Z}_{fs} = \left(\left\{K_{fseff} * \left(Z_{fu} - (Z_{fs} + \theta * a)\right) * \cos\varphi\right\} + \left\{C_{fs} * \left(\dot{Z}_{fu} - (\dot{Z}_{fs} + \dot{\theta} * a)\right)\right\} - \left\{\frac{F_{bf} * h}{a+b}\right\} - \{m_{fs} * g\}\right)$$
- $$m_{rs} * \ddot{Z}_{rs} = \left(\{K_{rs} * (Z_{ru} - (Z_{rs} + \theta * b)) * \cos\varphi\} + \left\{C_{rs} * \left(\dot{Z}_{ru} - (\dot{Z}_{rs} + \dot{\theta} * b)\right)\right\} + \left\{\frac{F_{bf} * h}{a+b}\right\} - \{m_{rs} * g\}\right)$$
- $$I_{yy} * \ddot{\theta} = \\ \left[\left(\left\{K_{fseff} * \left(Z_{fu} - (Z_{fs} + \theta * a)\right) * \cos(\varphi) * a\right\} + \left\{C_{fs} * \left(\dot{Z}_{fu} - (\dot{Z}_{fs} + \dot{\theta} * a)\right) * a\right\} - \left\{\frac{F_{bf} * h}{a+b}\right\} * a - \{m_{fs} * g * a\}\right)\right] - \\ \left[\left(\{K_{rs} * (Z_{ru} - (Z_{rs} + \theta * b)) * \cos(\varphi) * b\} + \left\{C_{rs} * \left(\dot{Z}_{ru} - (\dot{Z}_{rs} + \dot{\theta} * b)\right) * b\right\} + \left\{\frac{F_{bf} * h}{a+b}\right\} * b - \{m_{rs} * g * b\}\right)\right]$$
- $$m_s * \ddot{Z}_t = \begin{bmatrix} \left(\left\{K_{fseff} * \left(Z_{fu} - (Z_{fs} + \theta * a)\right) * \cos\varphi\right\} + \left\{C_{fs} * \left(\dot{Z}_{fu} - (\dot{Z}_{fs} + \dot{\theta} * a)\right)\right\} - \left\{\frac{F_{bf} * h}{a+b}\right\} - \{m_{fs} * g\}\right) + \\ + \left(\{K_{rs} * (Z_{ru} - (Z_{rs} + \theta * b)) * \cos\varphi\} + \left\{C_{rs} * \left(\dot{Z}_{ru} - (\dot{Z}_{rs} + \dot{\theta} * b)\right)\right\} + \left\{\frac{F_{bf} * h}{a+b}\right\} - \{m_{rs} * g\}\right) \end{bmatrix}$$
- $$F_{bf} = \frac{\left[(P_{brakeline} * 100{,}000) * \left(2\pi\left(\left(\frac{d_{p1}{}^2}{4}\right) + \left(\frac{d_{p2}{}^2}{4}\right)\right)\right) * \mu_{pad} * \left(\frac{d_{disc} - h_{pad}}{2 - g_{pad}}\right)\right]}{\left[\frac{t_{fw} * \frac{t_{fa}}{100} * 2 + t_{fd} * 24.5}{2000}\right]}$$

Figure 7-7 - Viva Slide 6

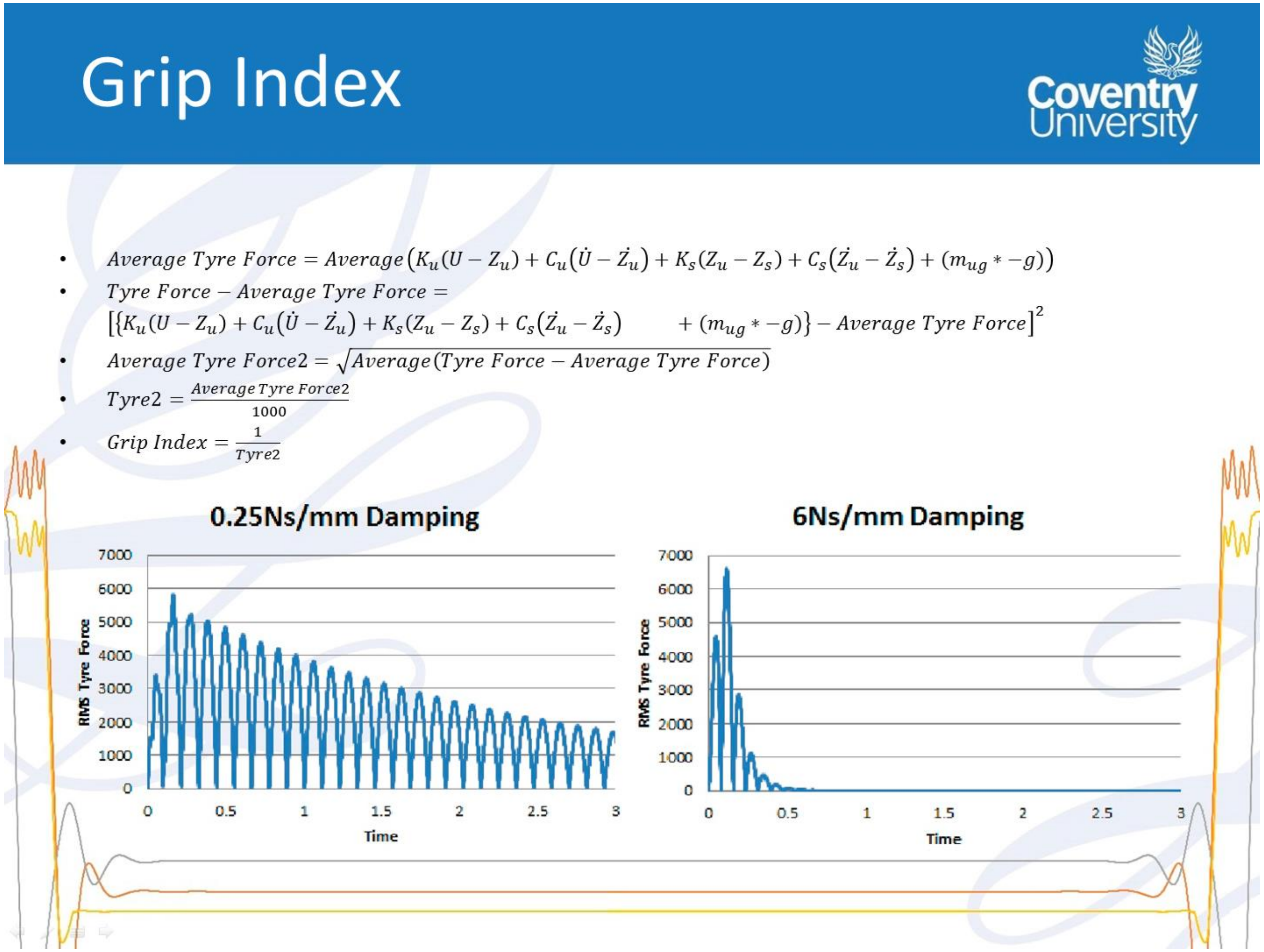


Figure 7-8 - Viva Slide 7

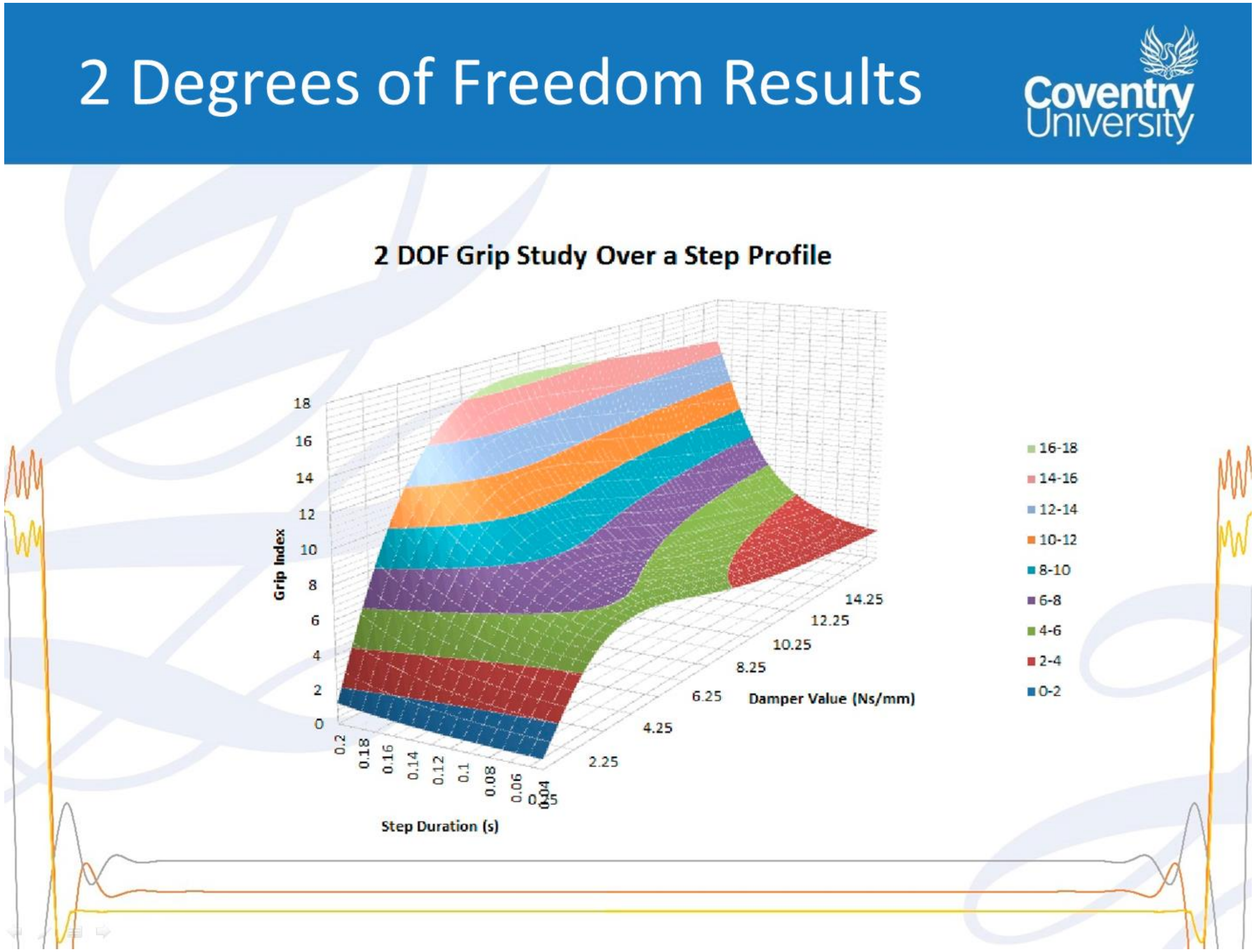


Figure 7-9 - Viva Slide 10

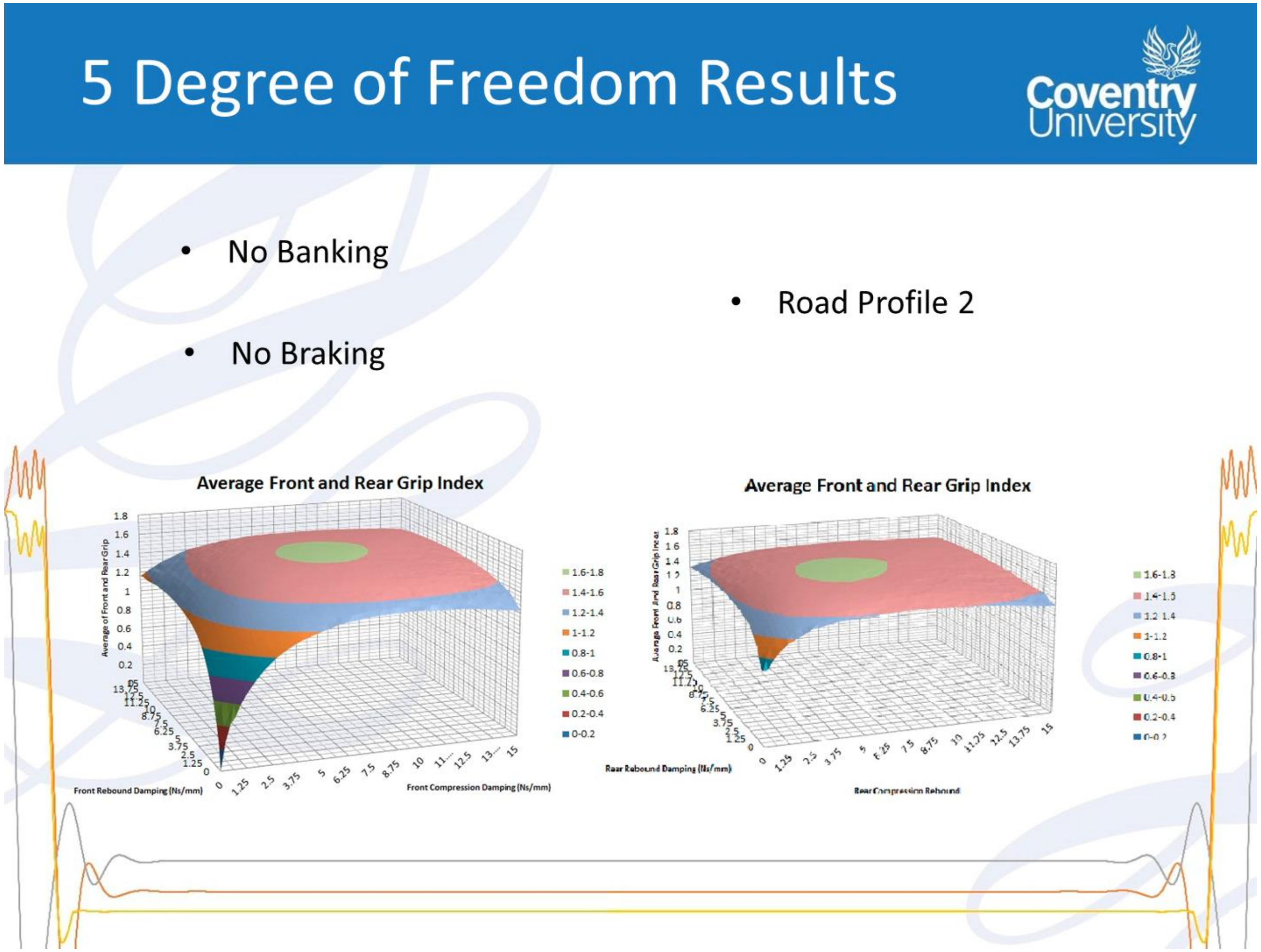


Figure 7-10 - Viva Slide 11

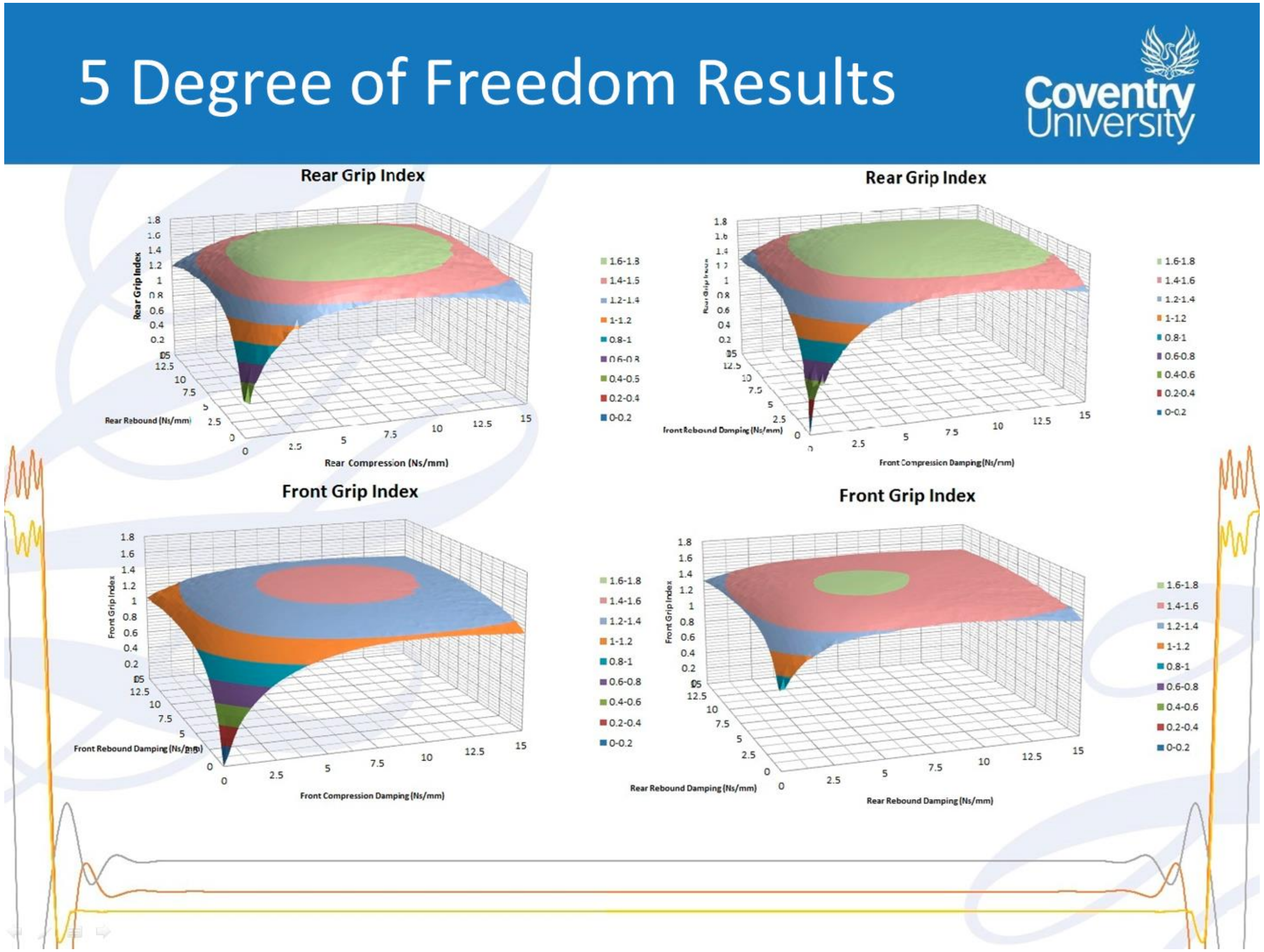


Figure 7-11 - Viva Slide 12

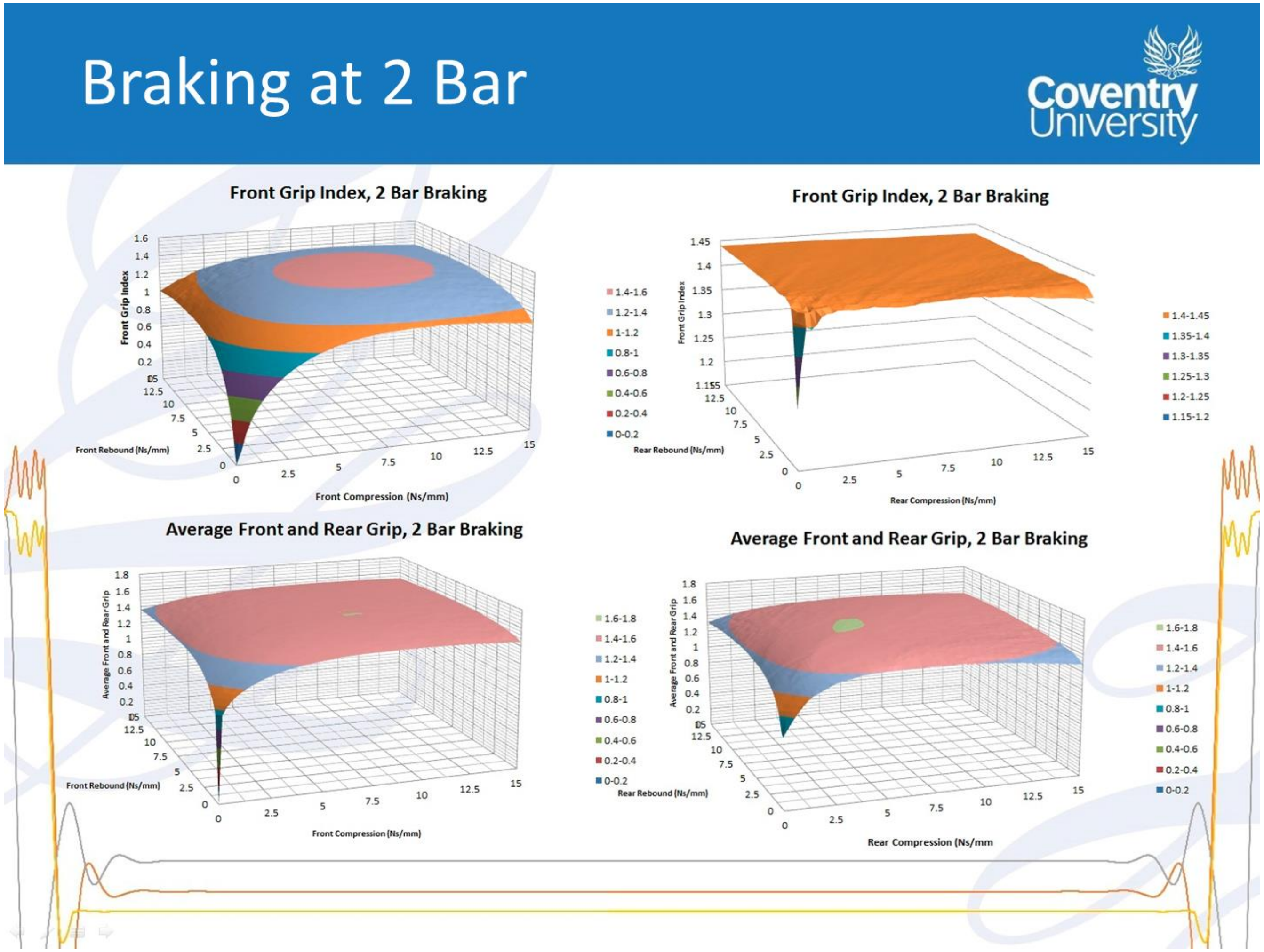


Figure 7-12 - Viva Slide 13

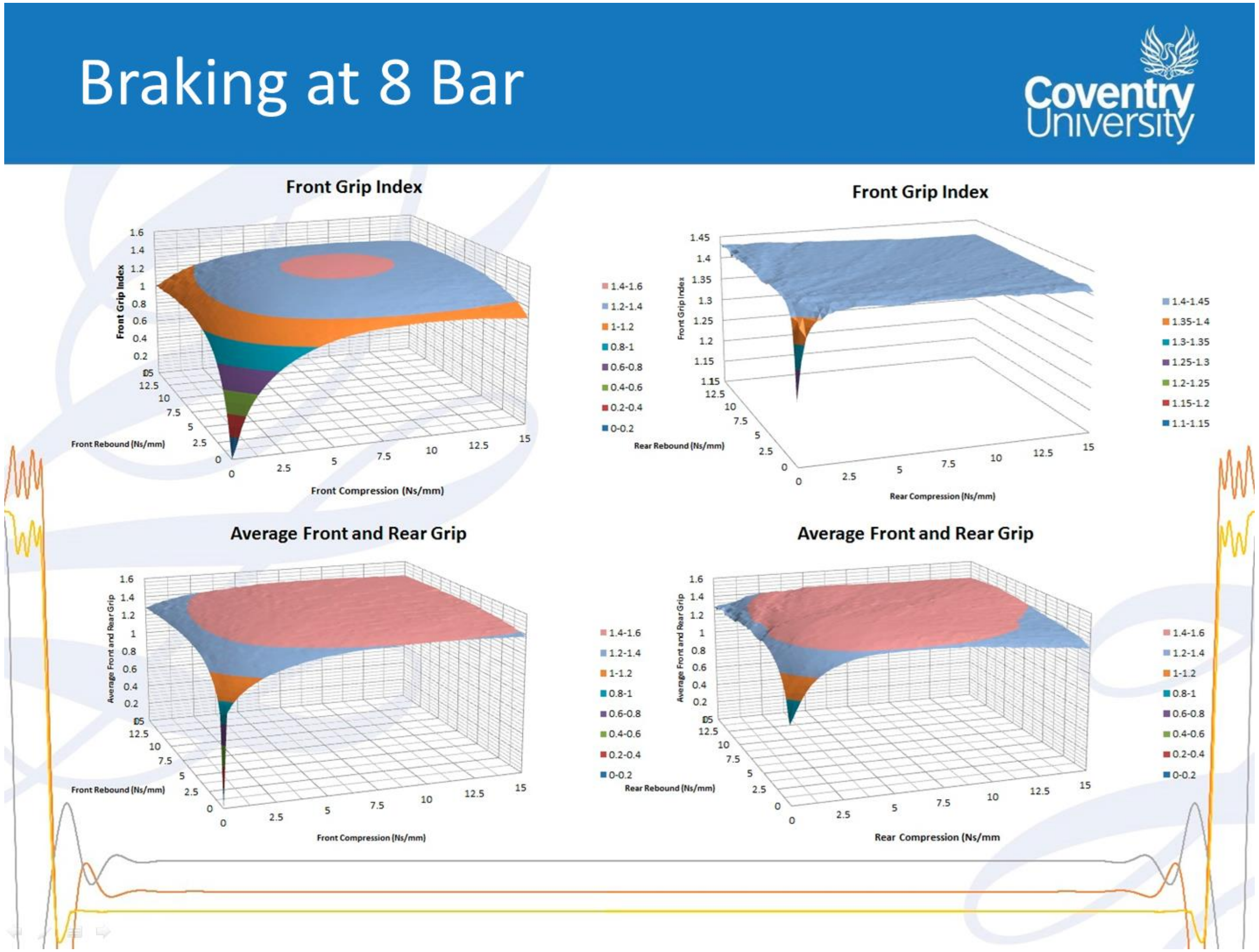


Figure 7-13 - Viva Slide 14

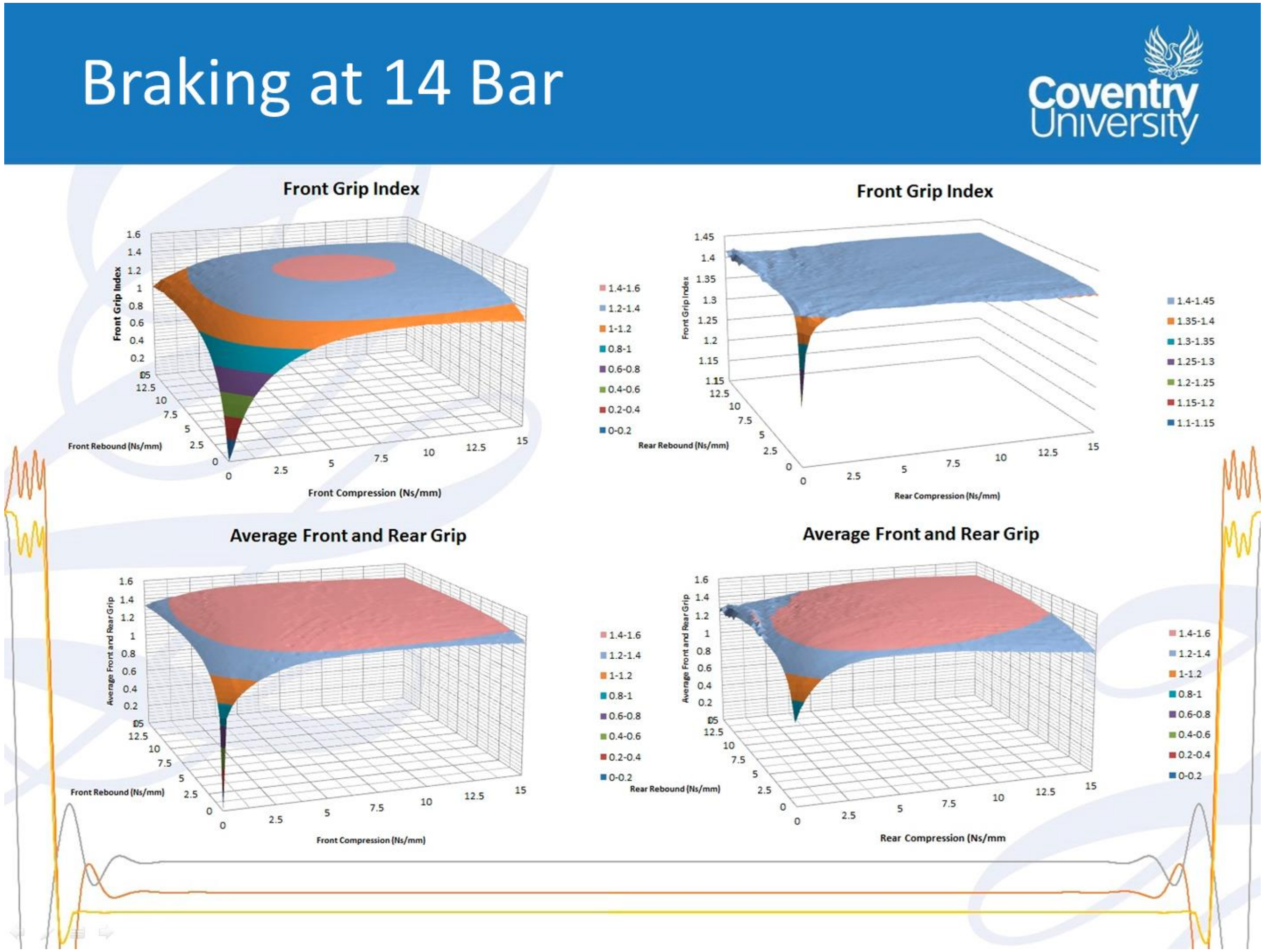
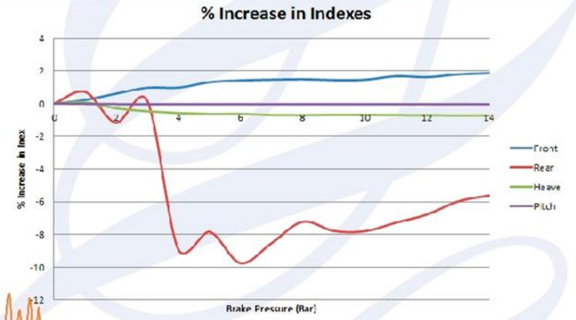


Figure 7-14 - Viva Slide 15

Varying Brake Pressure



Road Profile	Brake Pressure	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Random Road 2, Braking Pressure										
Road 2	0	7.096	7.218	5.107	2.322	1.4432	1.719	4.908	4.996	1.581
Road 2	1	7.096	7.218	5.107	2.322	1.4432	1.718	4.908	4.996	1.581
Road 2	2	7.318	7.152	4.153	1.721	1.4439	1.655	4.906	4.996	1.550
Road 2	3	7.318	7.152	4.153	1.721	1.4440	1.655	4.906	4.996	1.549
Road 2	4	7.484	6.883	4.682	0.500	1.4442	1.486	4.905	4.996	1.465
Road 2	5	7.288	6.970	4.649	0.500	1.4443	1.485	4.904	4.996	1.465
Road 2	6	7.407	6.933	3.960	0.500	1.4445	1.459	4.903	4.996	1.452
Road 2	7	7.352	6.946	3.948	0.500	1.4443	1.459	4.904	4.996	1.452
Road 2	8	7.336	6.948	3.944	0.500	1.4442	1.459	4.904	4.996	1.452
Road 2	9	7.316	6.962	3.930	0.500	1.4443	1.460	4.904	4.996	1.452
Road 2	10	7.323	6.959	3.921	0.500	1.4443	1.460	4.904	4.996	1.452
Road 2	11	7.326	6.947	3.892	0.500	1.4443	1.457	4.904	4.996	1.450
Road 2	12	7.320	6.955	3.887	0.500	1.4442	1.456	4.904	4.996	1.450
Road 2	13	7.324	6.953	3.984	0.500	1.4442	1.463	4.904	4.996	1.454
Road 2	14	7.327	6.950	3.979	0.500	1.4442	1.462	4.904	4.996	1.453

Road Profile	Brake Pressure	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	
Random Road 2, 6 Bar of Braking Pressure										
Road 2	0	7.096	7.218	5.107	2.322	1.4432	1.719	4.908	4.996	[illegible]
Road 2	1	7.096	7.218	5.107	2.322	1.4401	1.706	4.904	4.997	1.573
Road 2	2	7.096	7.218	5.107	2.322	1.4352	1.675	4.920	4.998	1.555
Road 2	3	7.096	7.218	5.107	2.322	1.4301	1.652	4.929	4.998	1.541
Road 2	4	7.096	7.218	5.107	2.322	1.4304	1.631	4.933	4.998	1.531
Road 2	5	7.096	7.218	5.107	2.322	1.4257	1.611	4.936	4.998	1.519
Road 2	6	7.096	7.218	5.107	2.322	1.4244	1.617	4.935	4.998	1.521
Road 2	7	7.096	7.218	5.107	2.322	1.4236	1.595	4.938	4.998	1.509
Road 2	8	7.096	7.218	5.107	2.322	1.4231	1.573	4.939	4.998	1.498
Road 2	9	7.096	7.218	5.107	2.322	1.4239	1.583	4.938	4.998	1.504
Road 2	10	7.096	7.218	5.107	2.322	1.4236	1.583	4.938	4.998	1.504
Road 2	11	7.096	7.218	5.107	2.322	1.4205	1.571	4.939	4.998	1.496
Road 2	12	7.096	7.218	5.107	2.322	1.4213	1.562	4.939	4.998	1.491
Road 2	13	7.096	7.218	5.107	2.322	1.4189	1.556	4.940	4.998	1.488
Road 2	14	7.096	7.218	5.107	2.322	1.4179	1.549	4.940	4.998	1.483

Figure 7-15 - Viva Slide 16

Bank Angle

Road Profile	Bank Angle		Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Random Road 2, Bank Angle											
Road 2	0		6.834	6.397	5.334	4.926	1.4399	1.784	4.910	4.996	1.612
Road 2	10		6.813	6.381	5.306	4.940	1.4450	1.790	4.910	4.996	1.618
Road 2	20		6.766	6.374	5.300	4.831	1.4606	1.809	4.908	4.996	1.635
Road 2	30		6.699	6.349	5.183	4.836	1.4865	1.839	4.906	4.996	1.663
Road 2	40		6.619	6.331	5.054	4.829	1.5232	1.882	4.902	4.996	1.703
Road 2	50		6.572	6.333	4.975	4.820	1.5705	1.938	4.896	4.996	1.754

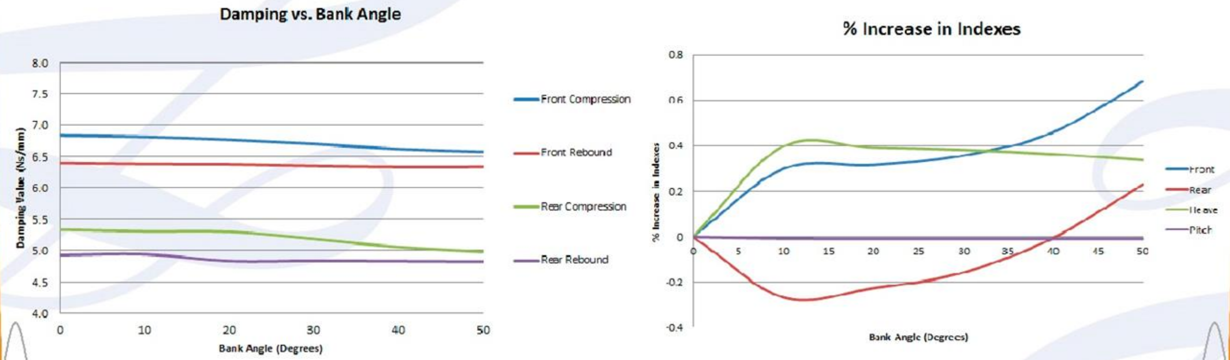


Figure 7-16 - Viva Slide 17

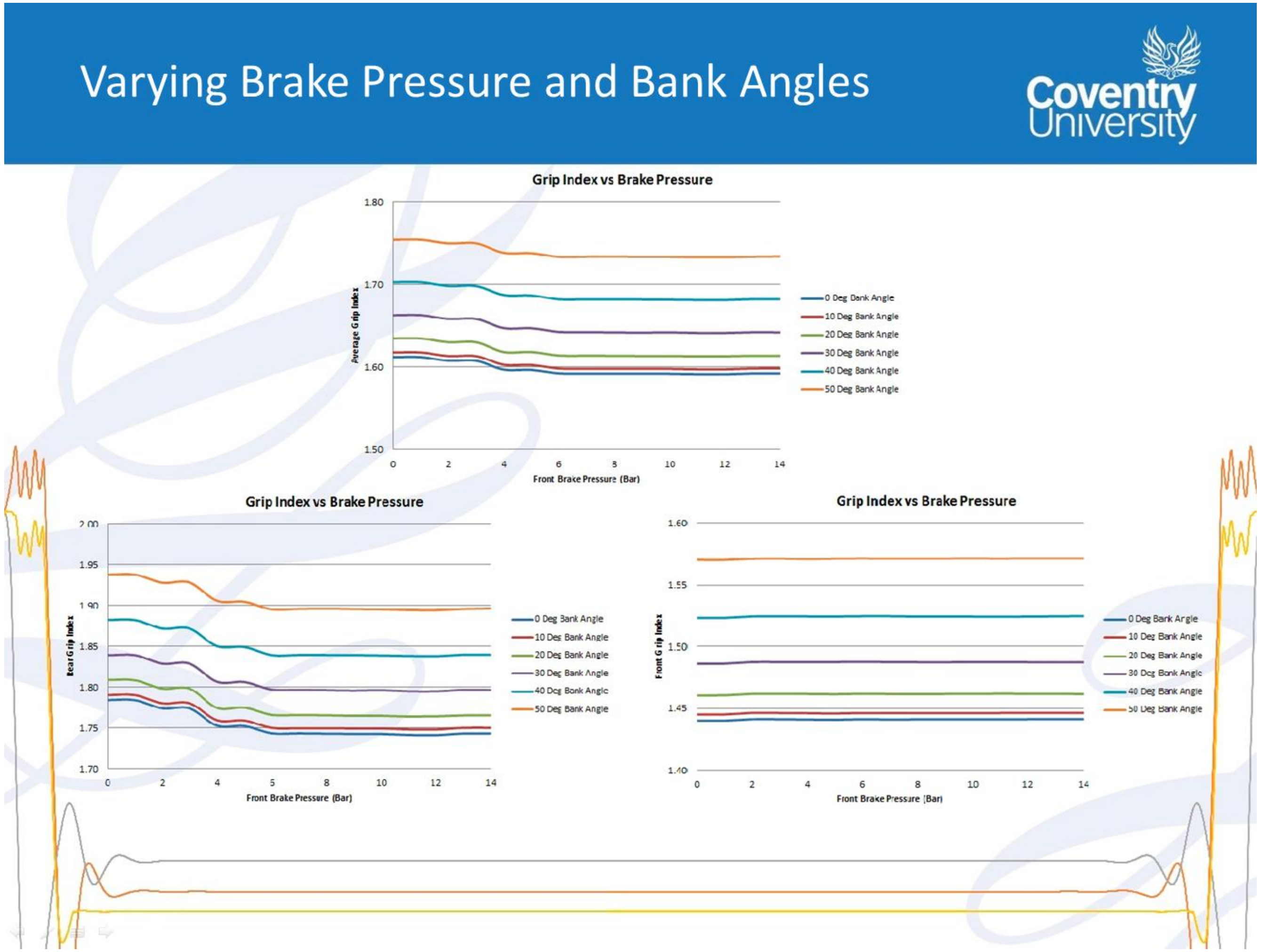


Figure 7-17 - Viva Slide 18

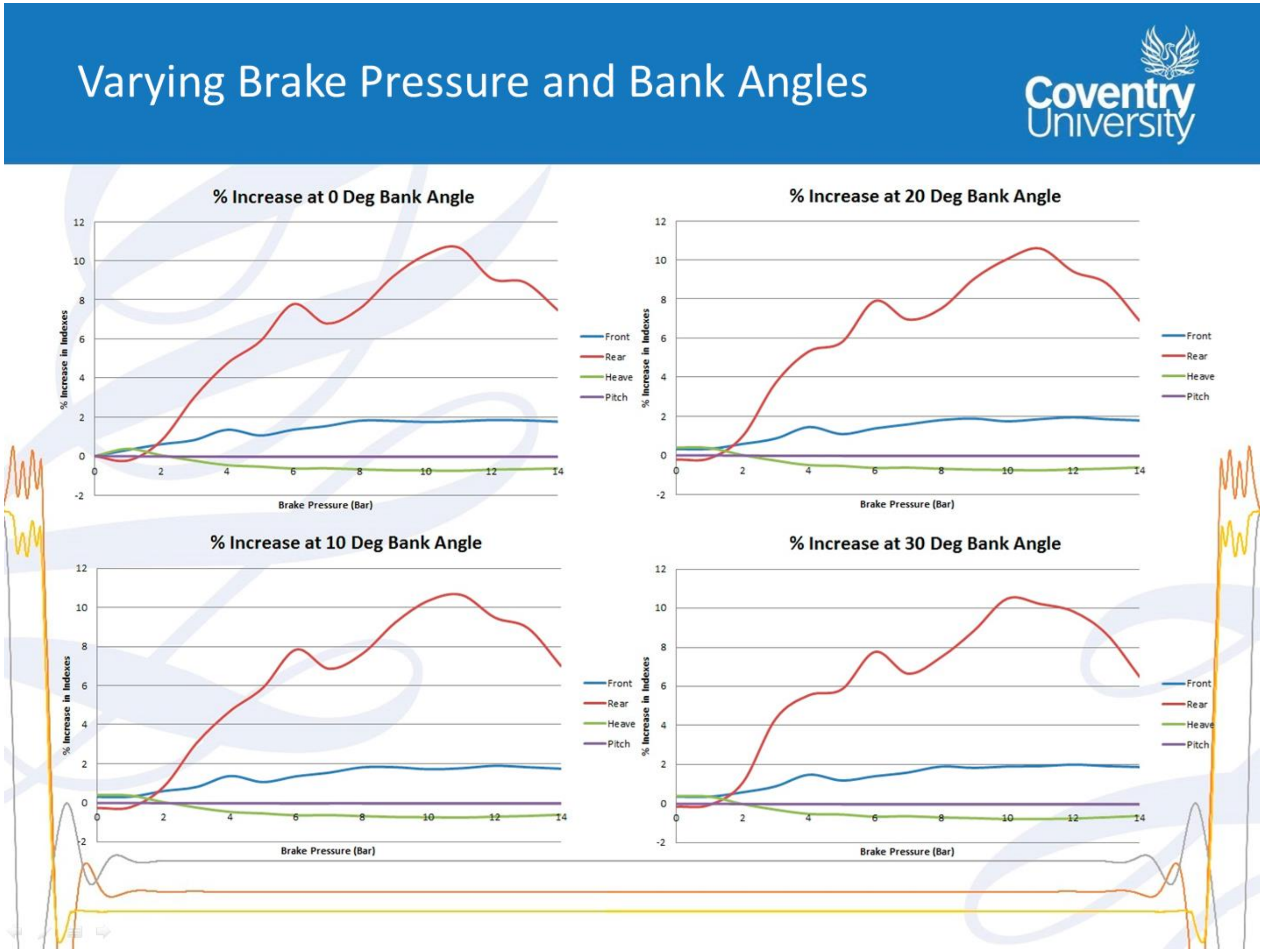


Figure 7-18 - Viva Slide 19

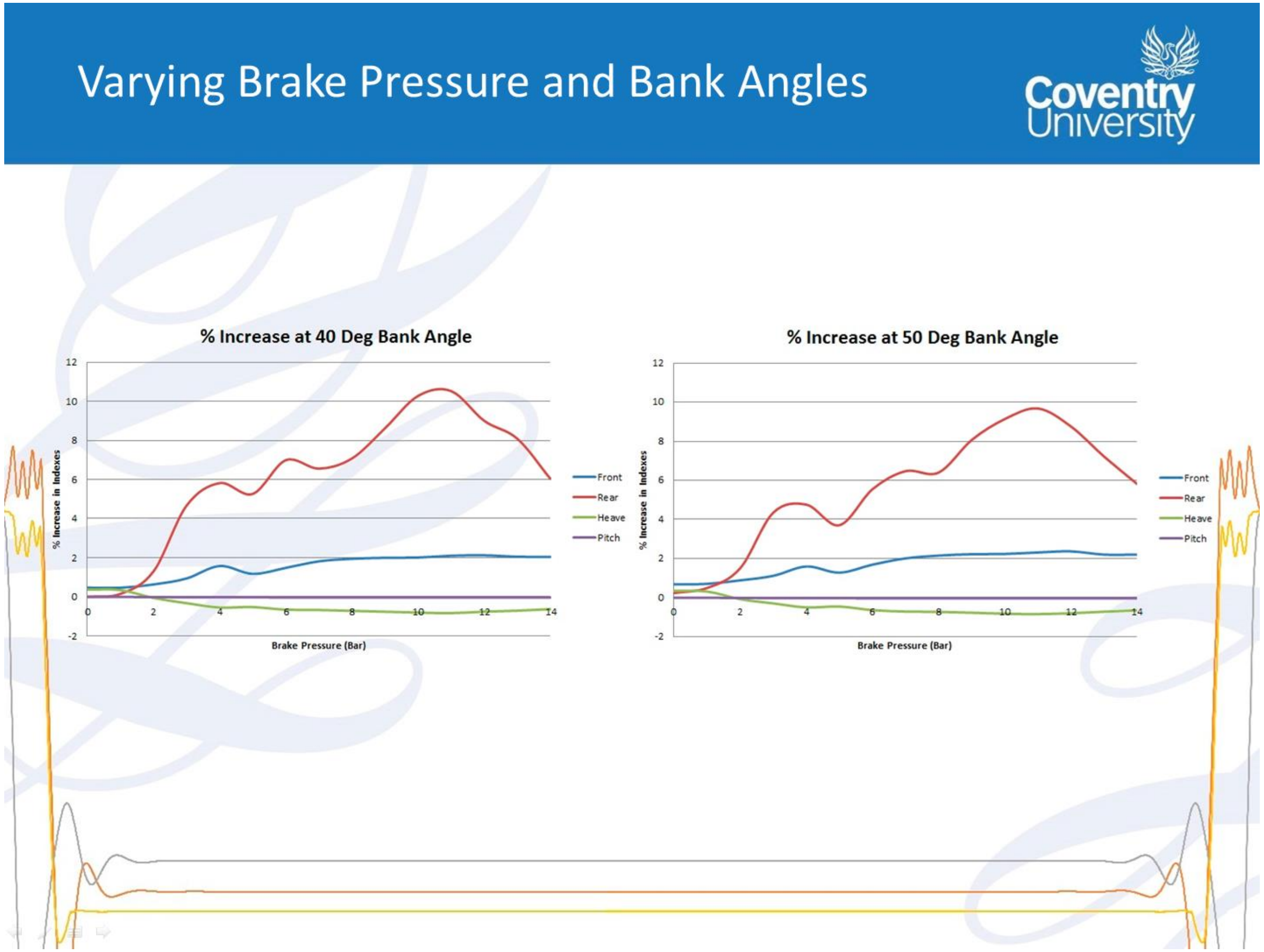


Figure 7-19 - Viva Slide 20

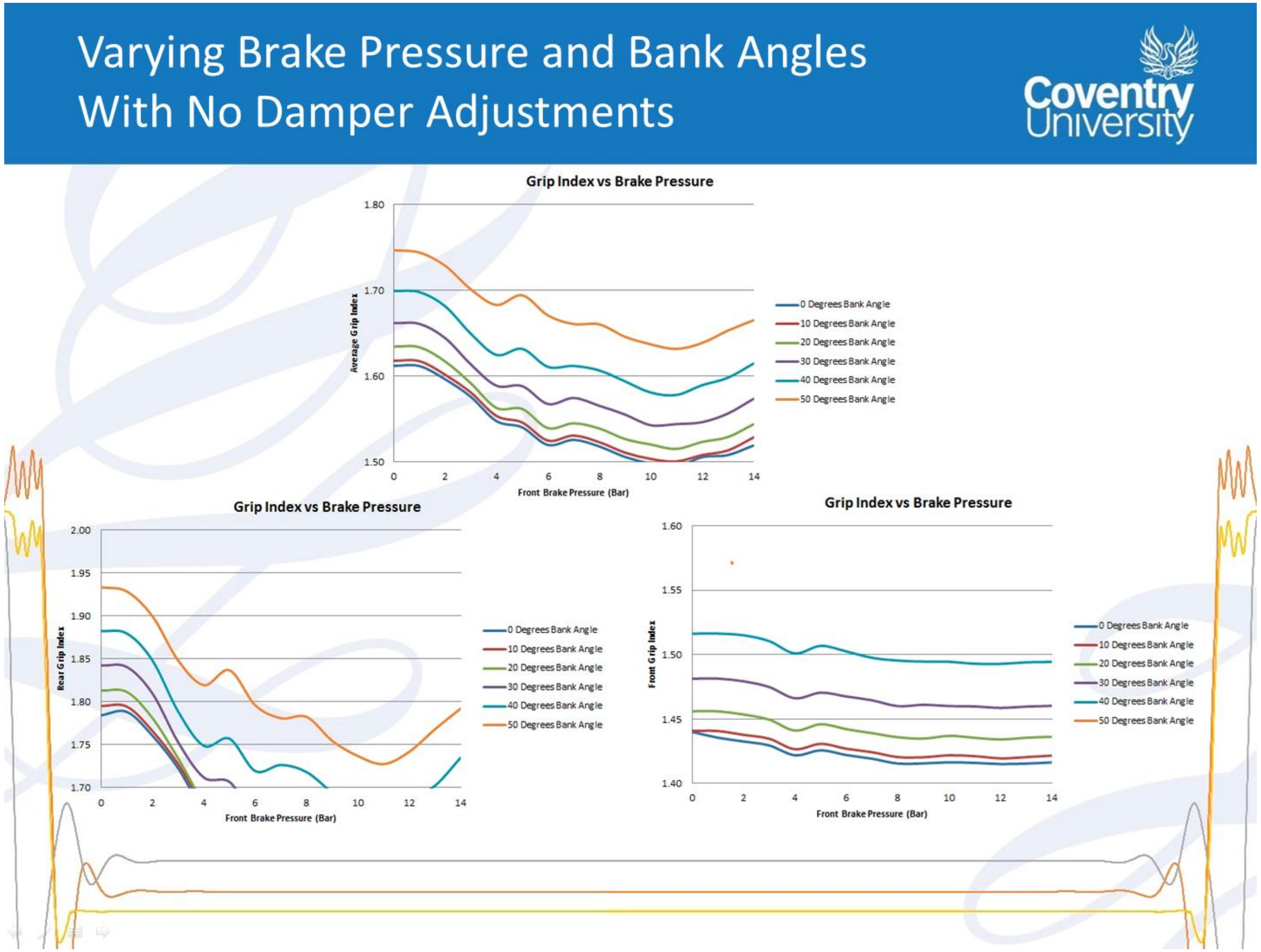


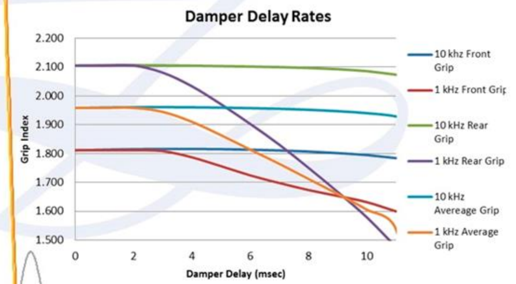
Figure 7-20 - Viva Slide 22

Damper Delay Rates

Coventry University

10,000 Hz Damper Delay Results, at 0 Braking Force and 0 Bank Angle										
Road Profile	Damper Delay (milli Second)	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Road 6	0	6.834	6.397	5.334	4.926	1.812	2.105	4.800	4.988	1.958
Road 6	1	6.834	6.397	5.334	4.926	1.814	2.106	4.807	4.988	1.960
Road 6	2	6.834	6.397	5.334	4.926	1.815	2.107	4.816	4.988	1.961
Road 6	3	6.834	6.397	5.334	4.926	1.816	2.106	4.824	4.988	1.961
Road 6	4	6.834	6.397	5.334	4.926	1.816	2.105	4.833	4.988	1.960
Road 6	5	6.834	6.397	5.334	4.926	1.815	2.103	4.842	4.988	1.959
Road 6	6	6.834	6.397	5.334	4.926	1.814	2.102	4.851	4.989	1.958
Road 6	7	6.834	6.397	5.334	4.926	1.811	2.100	4.861	4.989	1.955
Road 6	8	6.834	6.397	5.334	4.926	1.807	2.097	4.871	4.989	1.952
Road 6	9	6.834	6.397	5.334	4.926	1.802	2.092	4.881	4.989	1.947
Road 6	10	6.834	6.397	5.334	4.926	1.795	2.086	4.892	4.989	1.940
Road 6	11	6.834	6.397	5.334	4.926	1.784	2.073	4.903	4.989	1.929
Road 6	12	6.834	6.397	5.334	4.926	1.759	2.043	4.917	4.989	1.901

1,000 Hz Damper Delay Results, at 0 Braking Force and 0 Bank Angle										
Road Profile	Damper Delay (milli Second)	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Road 6	0	6.834	6.397	5.334	4.926	1.812	2.105	4.800	4.988	1.958
Road 6	1	6.834	6.397	5.334	4.926	1.812	2.105	4.800	4.988	1.958
Road 6	2	6.834	6.397	5.334	4.926	1.812	2.105	4.800	4.988	1.958
Road 6	3	6.834	6.397	5.334	4.926	1.809	2.081	4.830	4.988	1.945
Road 6	4	6.834	6.397	5.334	4.926	1.787	2.033	4.859	4.989	1.910
Road 6	5	6.834	6.397	5.334	4.926	1.756	1.971	4.889	4.989	1.864
Road 6	6	6.834	6.397	5.334	4.926	1.725	1.903	4.919	4.990	1.814
Road 6	7	6.834	6.397	5.334	4.926	1.698	1.831	4.949	4.990	1.764
Road 6	8	6.834	6.397	5.334	4.926	1.674	1.751	4.979	4.991	1.712
Road 6	9	6.834	6.397	5.334	4.926	1.653	1.667	5.008	4.991	1.660
Road 6	10	6.834	6.397	5.334	4.926	1.632	1.579	5.037	4.992	1.605
Road 6	11	6.834	6.397	5.334	4.926	1.600	1.476	5.065	4.993	1.538
Road 6	12	6.834	6.397	5.334	4.926	1.311	0.910	5.171	4.995	1.110



3ms Damper Delay Rate

Road Profile	Bank Angle	Damper Delay (milli Second)	Front Comp (Ns/mm)	Front Rebound (Ns/mm)	Rear Comp (Ns/mm)	Rear Rebound (Ns/mm)	Front Grip Index	Rear Grip Index	Heave Comfort Index	Pitch Comfort Index	Average Grip Index
Road 6	0	3	7.353	7.034	6.702	6.293	1.8169	2.110	4.840	4.989	1.964
Road 6	10	3	7.286	7.052	6.748	6.393	1.8189	2.113	4.840	4.989	1.966
Road 6	20	3	7.259	7.028	6.728	6.358	1.8251	2.119	4.836	4.988	1.972
Road 6	30	3	7.273	7.006	6.723	6.328	1.8355	2.129	4.831	4.988	1.982
Road 6	40	3	7.293	6.995	6.729	6.288	1.8494	2.143	4.822	4.987	1.996
Road 6	50	3	7.372	6.908	6.670	6.141	1.8664	2.159	4.809	4.986	2.013

Figure 7-21 - Viva Slide 23